DTNSRDC/SPD-0659-02

AD A108816

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Experimental Determination of Unsteady Forces on Contrarotating Propellers for Application to Torpedoes

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

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EXPERIMENTAL DETERMINATION OF UNSTEADY FORCES ON CONTRAROTATING PROPELLERS FOR APPLICATION TO TORPEDOES

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by

Marlin L. Miller

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Ship Performance Department
Departmental Report

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DECEMBER 1981 DTNSRDC/SPD-0659-02

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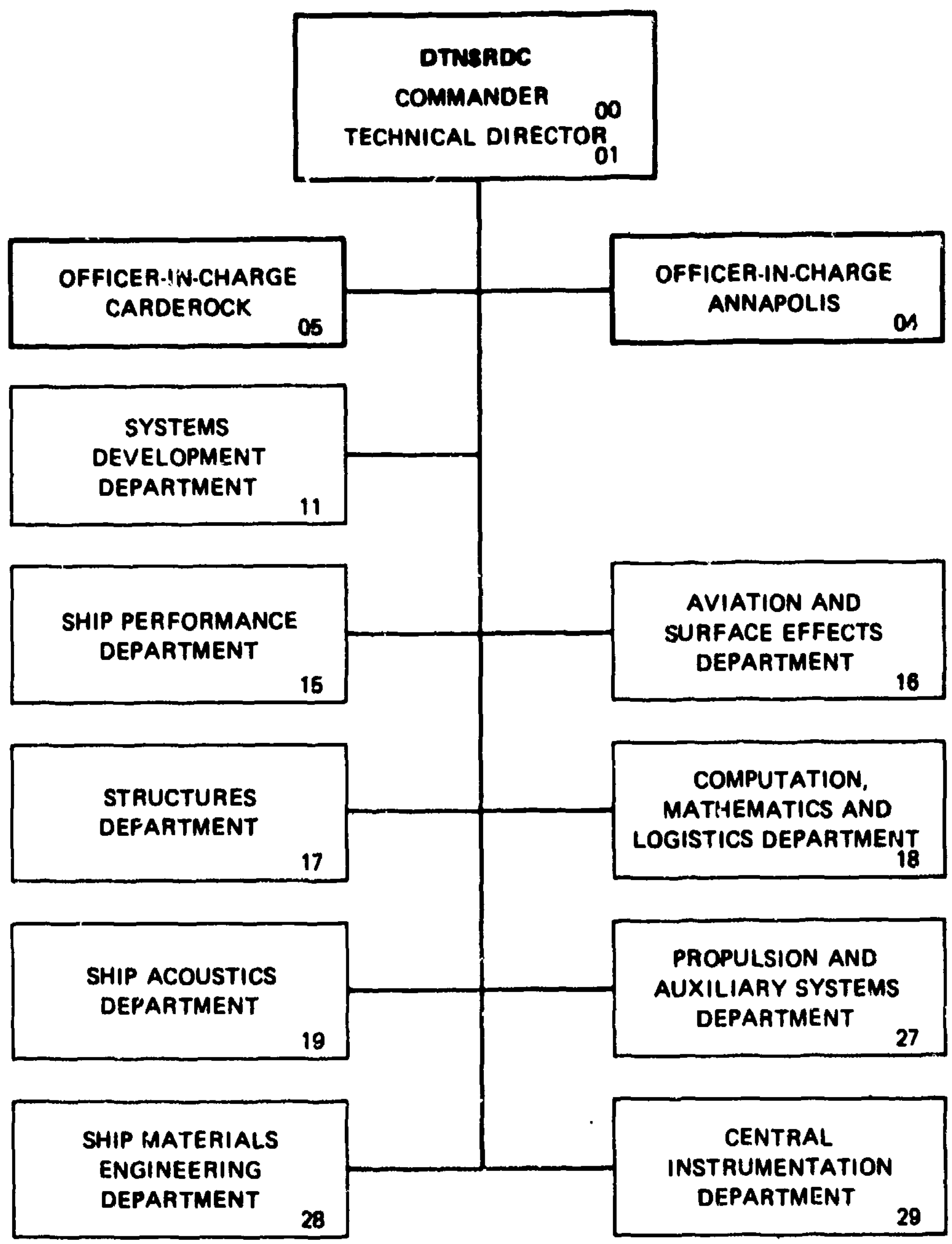
NDW-DTNSRDC 5602/30 (2-80)
(supersedes 3960/46)

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC/SPD-0659-02	2. GOVT ACCESSION NO. AD-A108816	3. RECIPIENT'S CATALOG NUMBER FINAL
4. TITLE (and Subtitle) Experimental Determination of Unsteady Forces on Contrarotating Propellers for Application to Torpedoes		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Marlin L. Miller		8. CONTRACT OR GRANT NUMBER(s) Program Element 61153N Project No. SR02301 Task No. SR0230103 Work Unit 1544-170
9. PERFORMING ORGANIZATION NAME AND ADDRESS David Taylor Naval Ship R&D Center Ship Performance Department Bethesda, MD 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command NAVSEA Code 63R31 (T. Peirce) Washington, D.C. 20362		12. REPORT DATE December 1981
		13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Propellers
Contrarotating Propellers
Hydrodynamics
Unsteady Propeller Forces

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents results of measurements of unsteady forces and moments on 4x4 and 4x5 bladed sets of contrarotating propellers in uniform flow and in a 4-cycle wake for application to torpedo propeller design. The uniform flow measurements were made to check earlier results that had been in disagreement with the results from calculations based on propeller theory. The uniform flow results confirmed the earlier results in showing larger forces on the forward propeller which is contrary to the prediction of existing theory. The results of the experiments in the 4-cycle wake showed unsteady forces on the

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forward propeller due to the effect of the wake along with the interaction forces between the two propellers. No theoretical calculations are available for comparison with the wake results.

The present procedure for conducting unsteady force and moment measurements on contrarotating propellers continues to be tedious and easily subject to error. Consequently, it is recommended that no further experiments be conducted using this procedure. It is recommended that for future experiments on contrarotating propellers the shafts be locked together mechanically and that a second dynamometer be used so that unsteady measurements can be made on both propellers simultaneously.

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NOTATION

A_N	Fourier cosine coefficient of unsteady loading
B_N	Fourier sine coefficient of unsteady loading
$C_{0.7}$	Chord length at 0.7R
D	Forward propeller diameter
$\tilde{F}_H$	Amplitude of unsteady horizontal side force
$\tilde{F}_V$	Amplitude of unsteady vertical side force
J	Advance coefficient, V_a/nD
$\tilde{K}_F$	Unsteady side force coefficient, $\tilde{F}/\rho n^2 D^4$
$\tilde{K}_M$	Unsteady bending moment coefficient, $\tilde{M}/\rho n^2 D^5$
K_Q	Steady torque coefficient, $Q/\rho n^2 D^5$
$\tilde{K}_Q$	Unsteady torque coefficient, $\tilde{Q}/\rho n^2 D^5$
K_T	Steady thrust coefficient, $T/\rho n^2 D^4$
$\tilde{K}_T$	Unsteady thrust coefficient, $\tilde{T}/\rho n^2 D^4$
$\tilde{M}_H$	Amplitude of unsteady horizontal bending moment
$\tilde{M}_V$	Amplitude of unsteady vertical bending moment
n	Rotational speed of propeller

N	Order of shaft frequency harmonic
Q	Steady component of torque
$\tilde{Q}$	Amplitude of unsteady compoent of torque
r	Radial coordinate
R	Radius of propeller
R_N	Reynolds number at 0.7R, $C_{0.7}[V_a^2 + (0.7\pi nD)^2]^{\frac{1}{2}} / \nu$
T	Steady component of thrust
$\tilde{T}$	Amplitude of unsteady component of thrust
V_a	Speed of advance
η	Propeller efficiency
θ	Angular position of propeller from upward vertical measured in the direction of propeller rotation
ν	Kinematic viscosity of the fluid
ρ	Mass density of the fluid
ϕ	Phase angle, arctan B_N/A_N
$\tilde{V}$	4-Cycle component of unsteady velocity
V_{CM}	Circumferential mean velocity
V_{VM}	Volume mean velocity

ABSTRACT

This report presents results of measurements of unsteady forces and moments on 4x4 and 4x5 bladed sets of contrarotating propellers in uniform flow and in a 4-cycle wake for application to torpedo propeller design. The uniform flow measurements were made to check earlier results that had been in disagreement with the results from calculations based on propeller theory. The uniform flow results confirmed the earlier results in showing larger forces on the forward propeller which is contrary to the prediction of existing theory. The results of the experiments in the 4-cycle wake showed unsteady forces on the forward propeller due to the effect of the wake along with the interaction forces between the two propellers. No theoretical calculations are available for comparison with the wake results.

The present procedure for conducting unsteady force and moment measurements on contrarotating propellers continues to be tedious and easily subject to error. Consequently, it is recommended that no further experiments be conducted using this procedure. It is recommended that for future experiments on contrarotating propellers the shafts be locked together mechanically and that a second dynamometer be used so that unsteady measurements can be made on both propellers simultaneously.

ADMINISTRATIVE INFORMATION

The work described in this report was sponsored by the Naval Sea Systems Command, Code 63R31 (formerly 03512), and funded under Program Element 61153N, Project No. SR 02301, David W. Taylor Naval Ship R&D Center, Work unit 1544-170.

INTRODUCTION

Marine propellers operating in a non-uniform flow as in the wake of a ship or torpedo experience an unsteady loading as the blades pass through the changing velocities in the wake. These unsteady forces are at multiples of shaft frequency and their magnitudes depend upon the magnitudes of the

harmonic components of the wake and the design of the propeller. The frequencies present depend upon the harmonic frequencies present in the wake and the number of blades on the propeller. With contrarotating propellers, additional frequencies are present due to the interaction between the propellers. The unsteady loading can cause a considerable amount of vibration and noise and it is important to be able to predict unsteady loads before selecting a propeller or set of propellers for a given application. Such predictions can be made experimentally by model tests or by calculations based on propeller theory.

A theory for single propellers has been developed and programmed and its validity has been partially confirmed by model experiments. However, a theory developed for contrarotating propellers[1,2*] produced results that were not in agreement with experimental results obtained in uniform flow. The results of these experiments have been reported in Reference 3.

There was a considerable difference between the magnitudes of the theoretical and the experimental results but the most disturbing difference was that while it was expected that the after propeller would show the greater unsteady forces due to interaction and the theoretical results confirmed this, the experimental results showed greater unsteady forces on the forward propeller.

Although the present experiments were planned to determine the unsteady forces on contrarotating propellers in a 4-cycle wake, there were also experiments made in uniform flow to check the earlier results.

*List of references are on page 11

EXPERIMENTAL APPARATUS AND WAKE

The experiments were performed in the 24-inch variable pressure water tunnel using the dynamometer and procedures described in references 3 and 4. As in the earlier experiments the one dynamometer had to be shifted from the upstream position to the downstream position so that the measurements on the two propellers had to be made at separate times. In this case the measurements were made about a year apart since sufficient funding was not available in one fiscal year. As recommended in reference 3, a fairing was used to enlarge the upstream shaft when the dynamometer was in the downstream position so that the upstream configuration was the same for the measurements on the two propeller and the flow into the propellers would be more nearly the same.

The four cycle wake was produced by four thick struts ahead of the propellers. Two existing thin struts 90 degrees apart had been used to support the dynamometer. They were thickened and two similar struts were added to form a symmetrical arrangement of four struts. A wake survey of the flow in the plane of the propellers was made to determine the flow produced by this arrangement. The results of this survey are shown in Figures 1 thru 5. The flow was found to have a nearly sinusoidal 4-cycle component of approximately four percent of the mean flow. There was also a small decrease in velocity radially from the propeller tip to the hub. These wake results for the 4-cycle component are shown in Figure 6. Not shown in this figure are some small higher frequency components. A

second harmonic was less than 12 percent of the 4-cycle amplitude and the third harmonic less than 3 percent.

UNSTEADY FORCE MEASUREMENTS

The first measurements were made in uniform flow to check the earlier results. The dynamometer was in the downstream position to measure the forces on the after propeller. Both 4x4 and 4x5 bladed propeller sets were used. The 4x4 set consisted of Propeller 3686 forward and 3687A in the after position. The 4x5 set used the same forward propeller with Propeller 3849 as the five bladed after propeller. Design details of these propellers are given in Tables 1,2 and 3 and their open water characteristics are shown in Figures 7 and 8. All of the propellers had zero skew.

Both propellers were run at a constant rotational speed of 12 revolutions per second for all experimental conditions and the water velocity was varied to produce loadings between zero thrust and a total K_T of approximately 0.50. Advance coefficient J and water velocity were determined by using a thrust identity between the total steady thrust and the total open water thrust. These conditions resulted in Reynolds numbers between 5.1 and 5.9 $\times 10^5$ at the 70% radius. The axial spacing between the propeller centerlines was held at 1.70 inches (0.043m). Steady thrust and torque were measured using the regular tunnel dynamometer. The six unsteady components of loading were measured using the six component unsteady dynamometer and were recorded on analog tape and later digitized.

The same problems of holding the propellers at exactly the same speed in order to prevent changes in the phase of the unsteady forces as reported in Reference 3 were experienced. In fact, the problem was somewhat greater than during the earlier experiments due to problems with the speed control of the tunnel drive motors. As before, this problem was partially eliminated by marking the analog tape with pulses indicating which revolutions of the propellers were in approximately the proper phase relationship. After both sets were run in uniform flow the wake producing struts were installed and the experiments were repeated in the 4-cycle wake.

The dynamometer was then moved to the upstream position (a year later) and the experiments were repeated to obtain measurements on the forward propeller.

The analog tapes were digitized, reading 100 of the marked in-phase revolutions for each condition and recording them on a digital tape. A computer program was used to average the readings, apply calibration corrections, and make a harmonic analysis of the unsteady forces and moments.

RESULTS

Figure 9 shows the unsteady thrust coefficient amplitudes and phase angle in uniform flow for the 4x4 propeller set at blade passing frequency (eight times shaft frequency). This condition was run to check earlier results in uniform flow.

The unsteady thrust coefficients and phase angles for the separate forward and after propeller were obtained directly from the computer

output. The computer output also gave the separate cosine and sine component amplitudes of unsteady thrust, A_N and B_N where in this case $N = 8$. To obtain total values for the propeller pair the components were added vectorially,

$$A\ total = A_{Forward} + A_{After}$$

and $$B\ total = B_{Forward} + B_{After}$$

Then $$K_{T_{Total}} = [A^2_{Total} + B^2_{Total}]^{1/2} / \rho n^2 D^4$$

And $$\phi_{Total} = \mathrm{Arctan}\left[B_{Total} / A_{Total}\right]$$

Angles are measured in the direction of forward propeller rotation from the upward vertical position of vector F_v in Figure 10. This figure also shows the directions for the positive values of the forces and moments. Figure 11 shows results for the unsteady torque.

For the 4x4 set, or for any set having equal numbers of blades, the only unsteady forces in uniform flow are thrust and torque. To observe unsteady side forces and bending moments certain unequal numbers of blades must be used. For these experiments the 4x5 set was selected. A discussion of which of the unsteady components are present and at which frequencies for any combination of blade numbers is given in Reference 5. For the 4x5 set the lowest frequency for the side forces and bending moments is nine times shaft frequency. Some higher frequencies for all six components are also present but they are well above the frequency range of the dynamometer.

Figures 12,13,14, and 15 show the vertical and horizontal side forces and bending moments and their phase angles for the 4x5 propeller set in uniform flow. These conditions were also run to check the earlier uniform flow experiments.

The remainder of the results are for the experiments in the 4-cycle wake. Figures 16 through 21 show the unsteady thrusts and torques for the 4x4 set at 4,8, and 16 times shaft frequency. Figures 22,23,24, and 25 show the unsteady thrusts and torques for the 4x5 set. In this case the 4x5 set shows unsteady thrusts and torques due to the 4-bladed forward propeller in the 4-cycle wake. Figures 26,27,28, and 29 show the unsteady side forces and bending moments generated by the interaction between the two propellers.

DISCUSSION OF RESULTS

The repeat experiments in uniform flow, Figures 9,11,12,13,14,15 show greater amplitudes for the unsteady forces on the forward propeller than the after propeller, as they did in the earlier results. The amplitudes are in fairly good agreement in the middle range of the loading (J values) but at zero and the greatest loads they are generally smaller than those of the earlier experiments. The bending moments on the forward propeller of the 4x5 set are so large in uniform flow that they appear to be in error. However, since the forward moments were also unusually large with the 4-cycle wake it is not likely they were in error for both conditions. The phase angles are generally in poorer agreement with the earlier

experiments than are the magnitudes. There appears to be no consistent trend in these differences. The best agreement for phase angles is in bending moments where the magnitude for the forward propeller showed the greatest difference. If the use of the fairing to increase the diameter of the forward shaft when the dynamometer was in the after position had any effect on the repeat experiments it would have been on the after propeller. However, no consistent difference in this direction was noted. In the 4-cycle wake the results were as expected. The 4x4 set showed the same unsteady thrusts and torques due to interaction as they had in uniform flow at the blade passing frequency of eight times shaft frequency and at its second harmonic of sixteen times shaft frequency. In addition there was a blade rate signal of four times shaft frequency on both propellers of the set due to the wake. The interaction forces agree well with those in uniform flow both in amplitude and phase.

The 4x5 set showed side forces and bending moments in fairly good agreement with those in uniform flow in magnitude although the phase angles were not in as good agreement. The bending moments on the forward propeller were again unexpectedly high, as they were in uniform flow. This had not occurred in the earlier experiments and no explanation has been found. The 4x5 set also showed unsteady thrusts and torque on the forward propeller at blade frequency due to the wake. Some 4-cycle thrusts and torques also appeared on the 5-bladed aft propeller. Although lower than those on the forward propeller, they were greater than expected. At eight times shaft frequency the unsteady thrusts were very small as was expected.

It will be noted that some of the curves are incomplete and several of the phase curves are missing completely. The reason for the incomplete curves is that some of the digital tapes were not analyzed until as long as two years after the data had been recorded and some of the markers attached to them to identify the records had become detached so that the data could not be identified. The phase results depend critically on the exact control of the propeller speeds and phase relationships. In several cases the phase curves were obviously in error and to avoid confusion, they are not shown. No results that appeared to be grossly in error were plotted.

CONCLUSION

The unsteady force experiments on contrarotating propellers were severely handicapped by the manner in which they had to be conducted. Using only one dynamometer and not being able to lock the propellers together at equal speeds and fixed phase relationships made it very tedious to conduct the experiments and the results are therefore easily subject to error. This is especially true for the side force and bending moment results and the total values for the combined propellers sets. These results were obtained from vector sums of two or four signals and are dependent upon good phase values and are most likely to be in error. It is difficult to estimate this error but it is believed that it could be as great as 20 percent. The individual thrust and torque results are less phase dependent and the error in these results may be as little as 10 percent.

It is very strongly recommended that no further experiments with contrarotating propellers be attempted using the existing equipment and procedures. The propellers should be locked together by a shaft outside the tunnel extending from one drive motor to the other. This shaft should carry enough driving torque so that all lost motion is taken up and a fixed phase relationship is preserved. A mechanical phase shifter in this shaft would permit setting the desired phase relationship each time the loading is changed. It is also desirable to have a second dynamometer so that readings from both propellers can be made at the same time to insure that the conditions are the same for both propellers.

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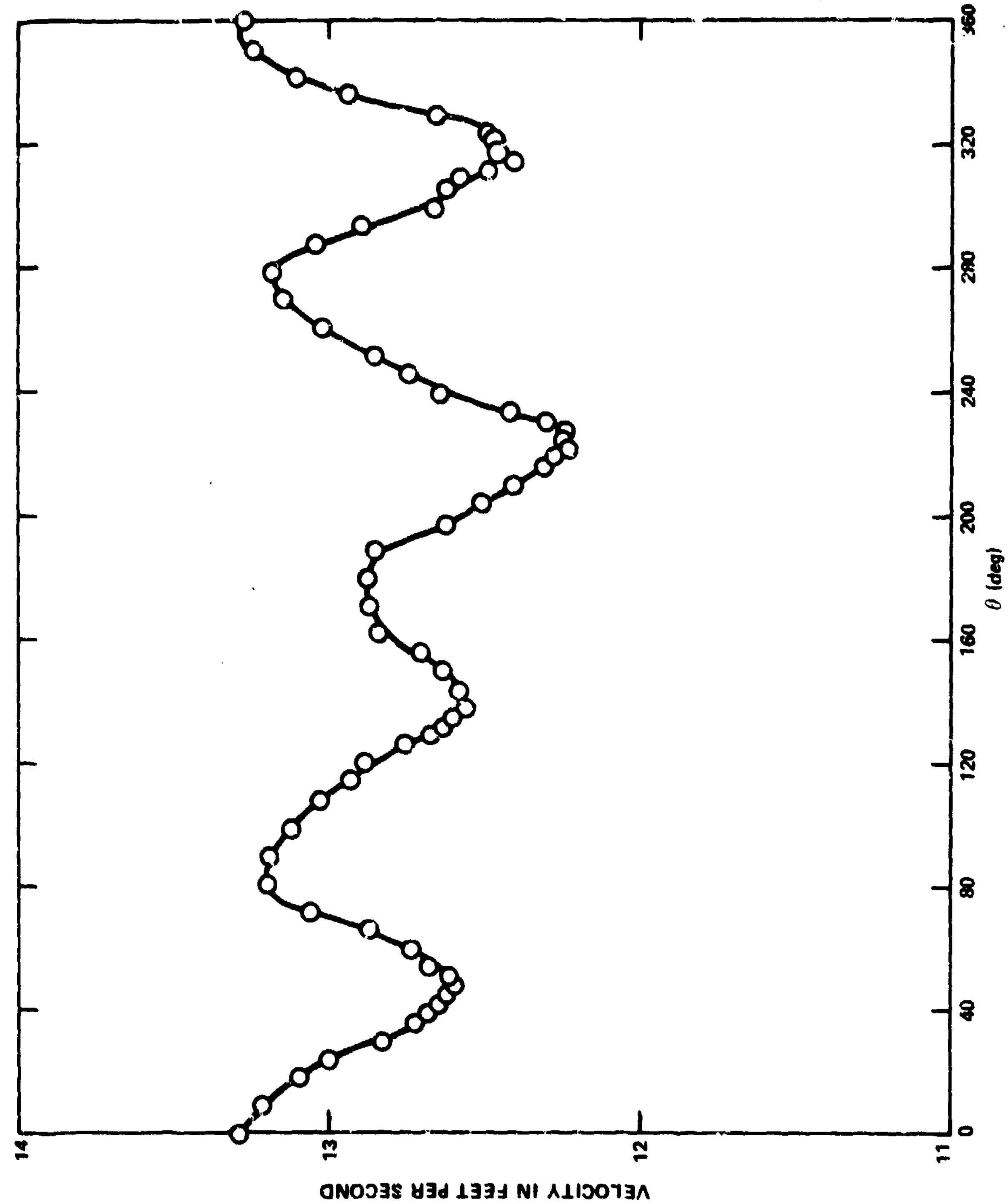


Figure 1 - Velocity Survey of 4-Cycle Wake at r/R = 1.023

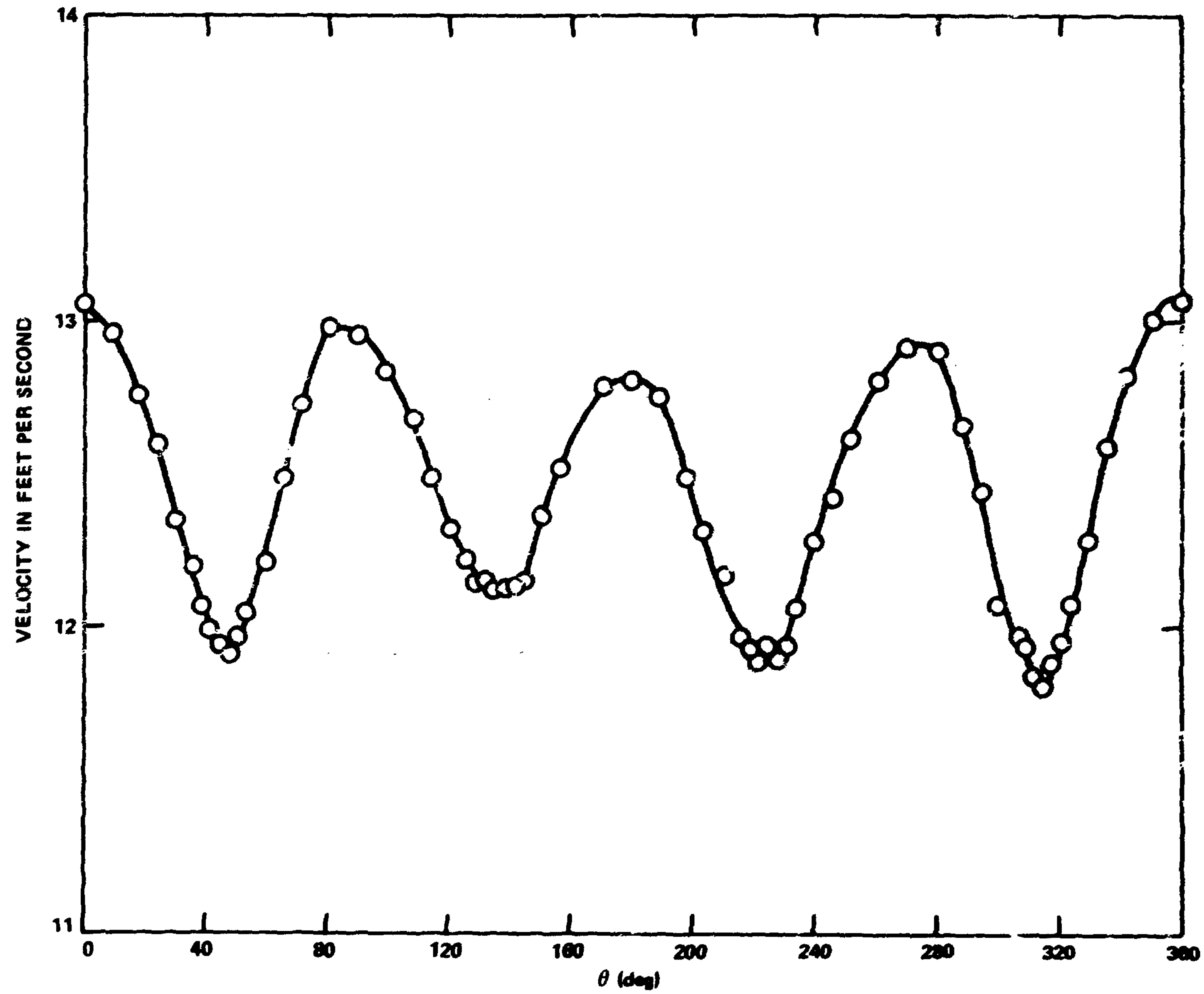


Figure 2 - Velocity Survey of 4-Cycle Wake at r/R = 0.862

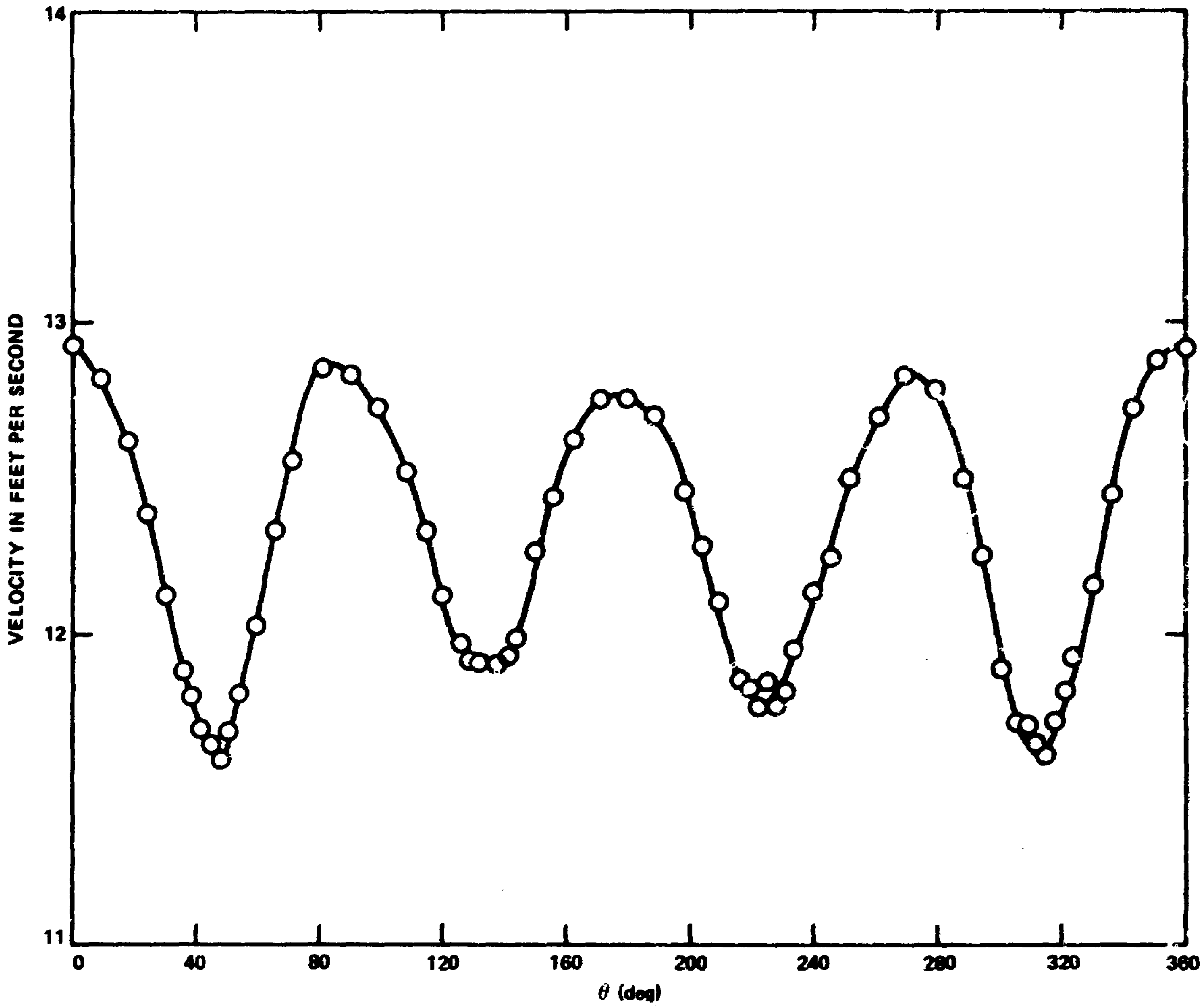


Figure 3 - Velocity Survey of 4-Cycle Wake at r/R = 0.712

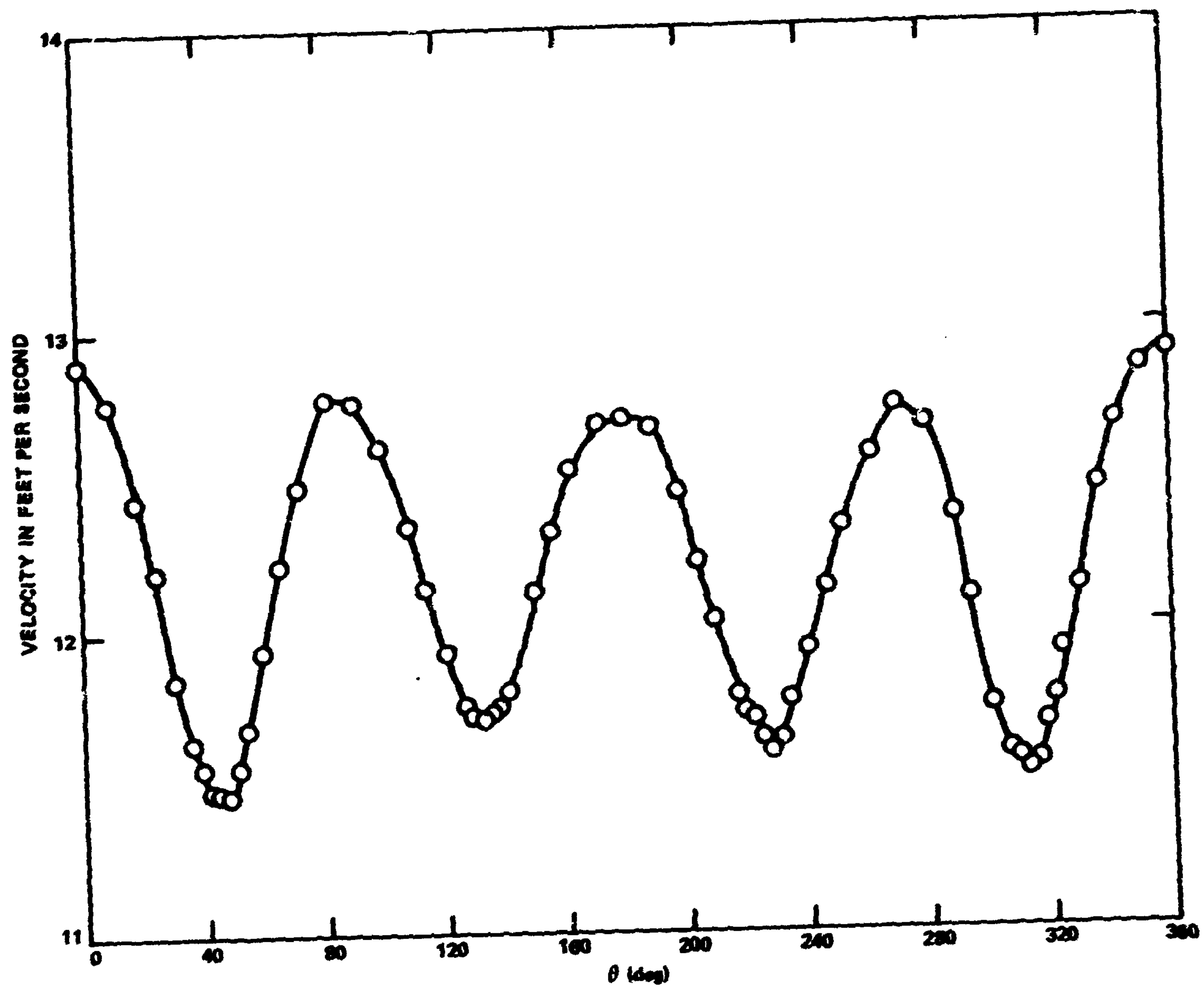


Figure 4 - Velocity Survey of 4-Cycle Wake at r/R = 0.526

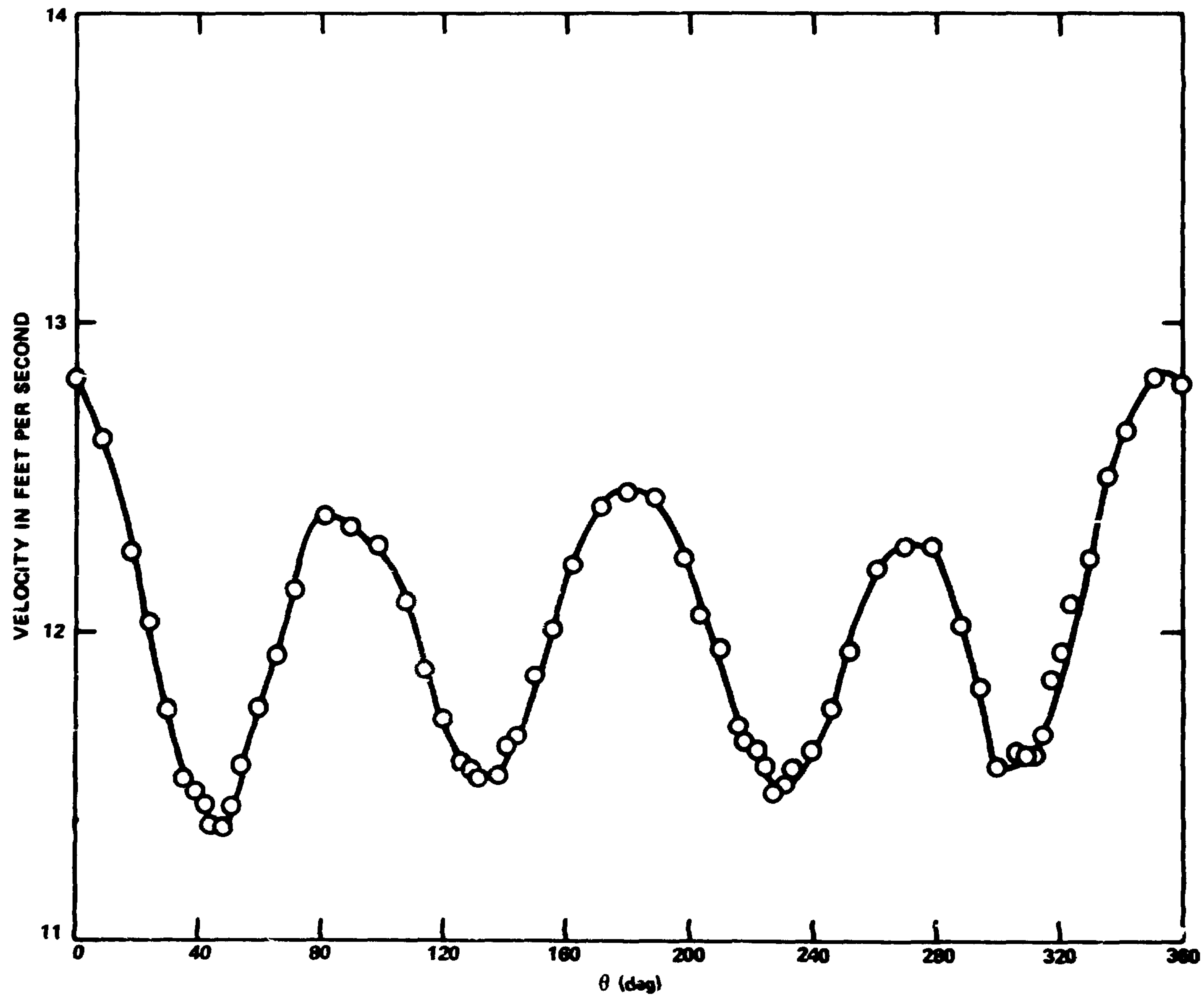


Figure 5 - Velocity Survey of 4-Cycle Wake at r/R = 0.308

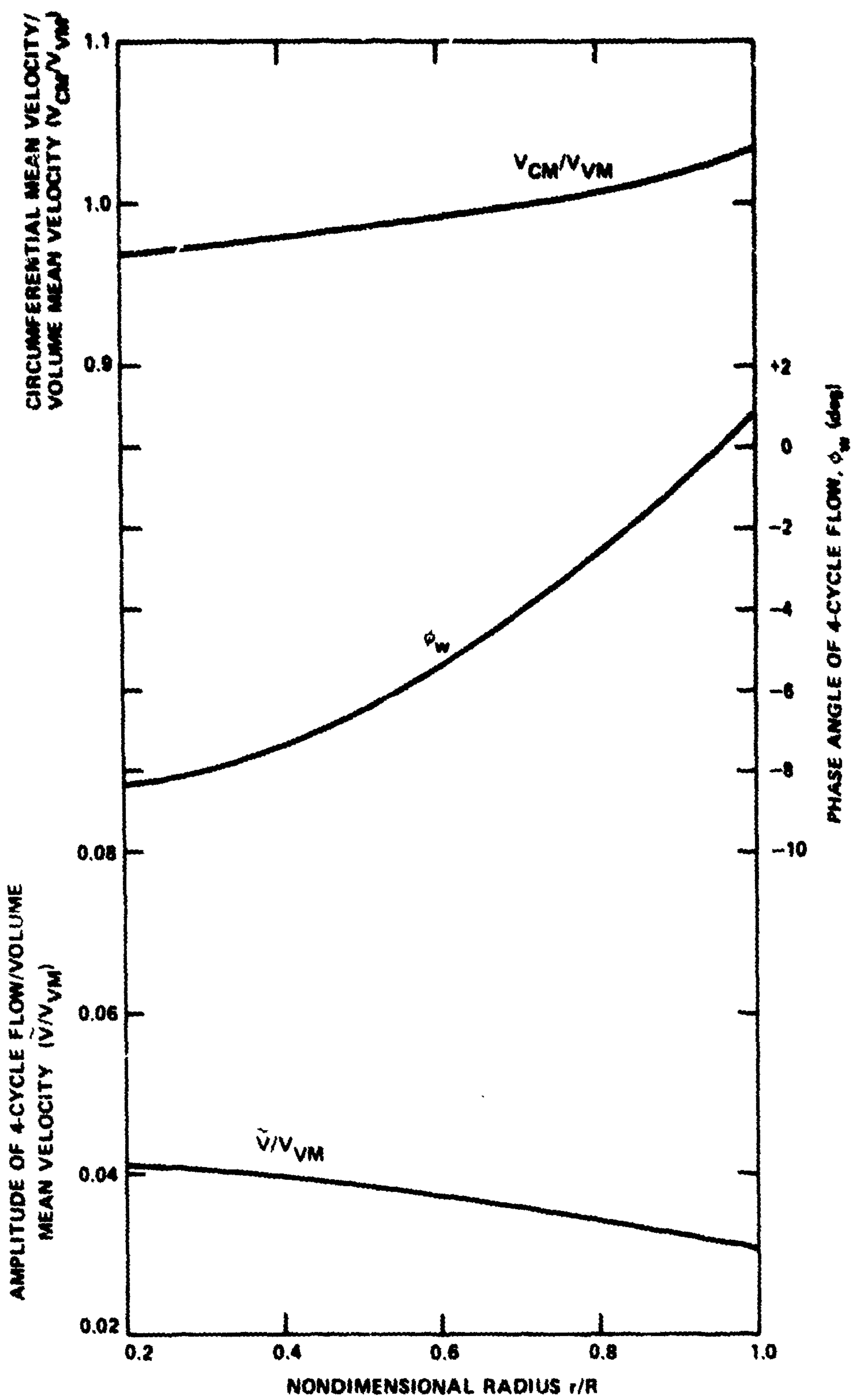


Figure 6 - Characteristics of 4-Cycle Wake

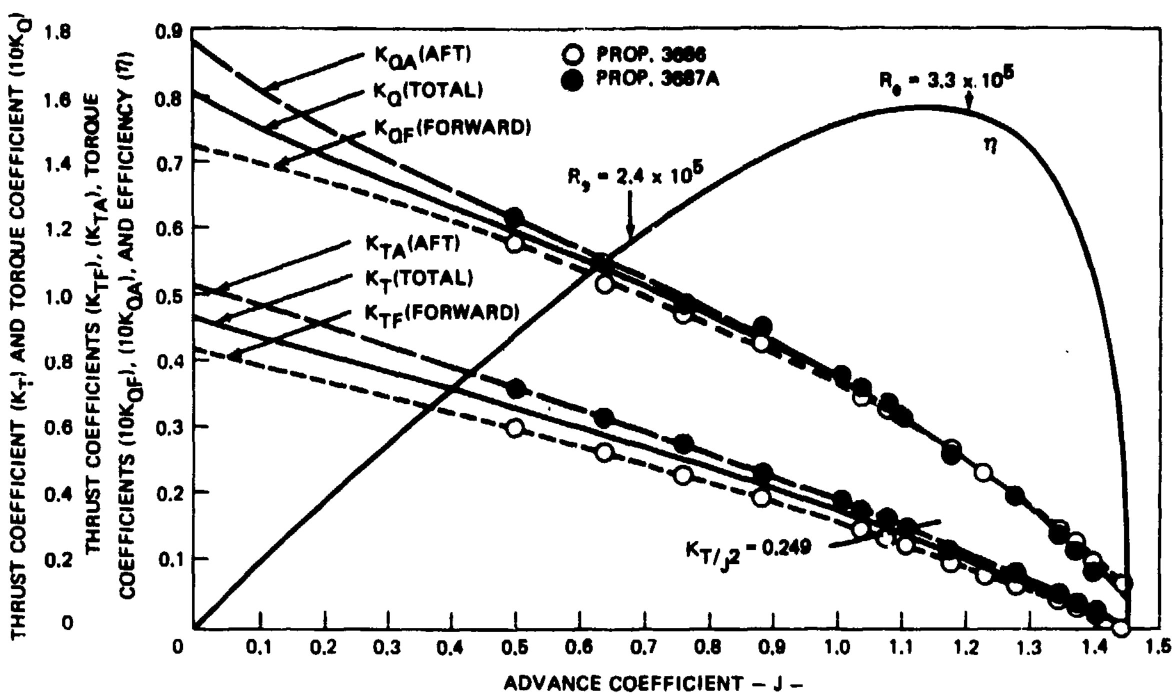


Figure 7 - Open Water Characteristics of Propellers 3686-87A

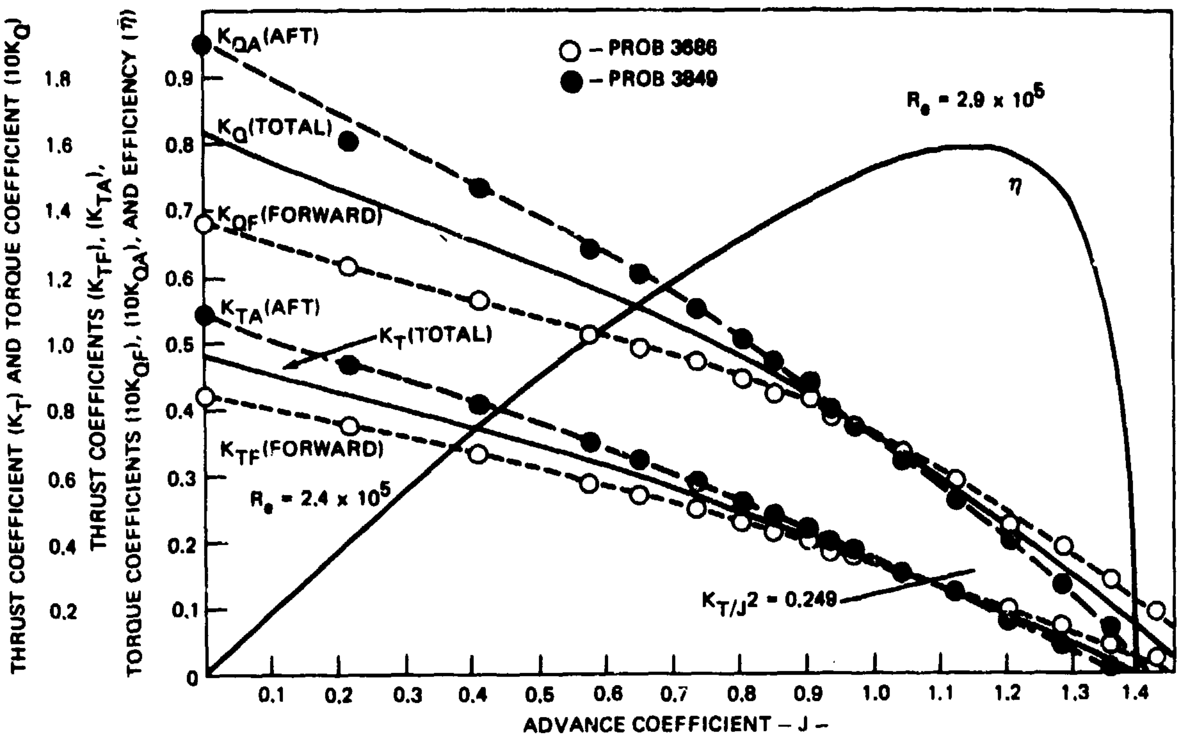
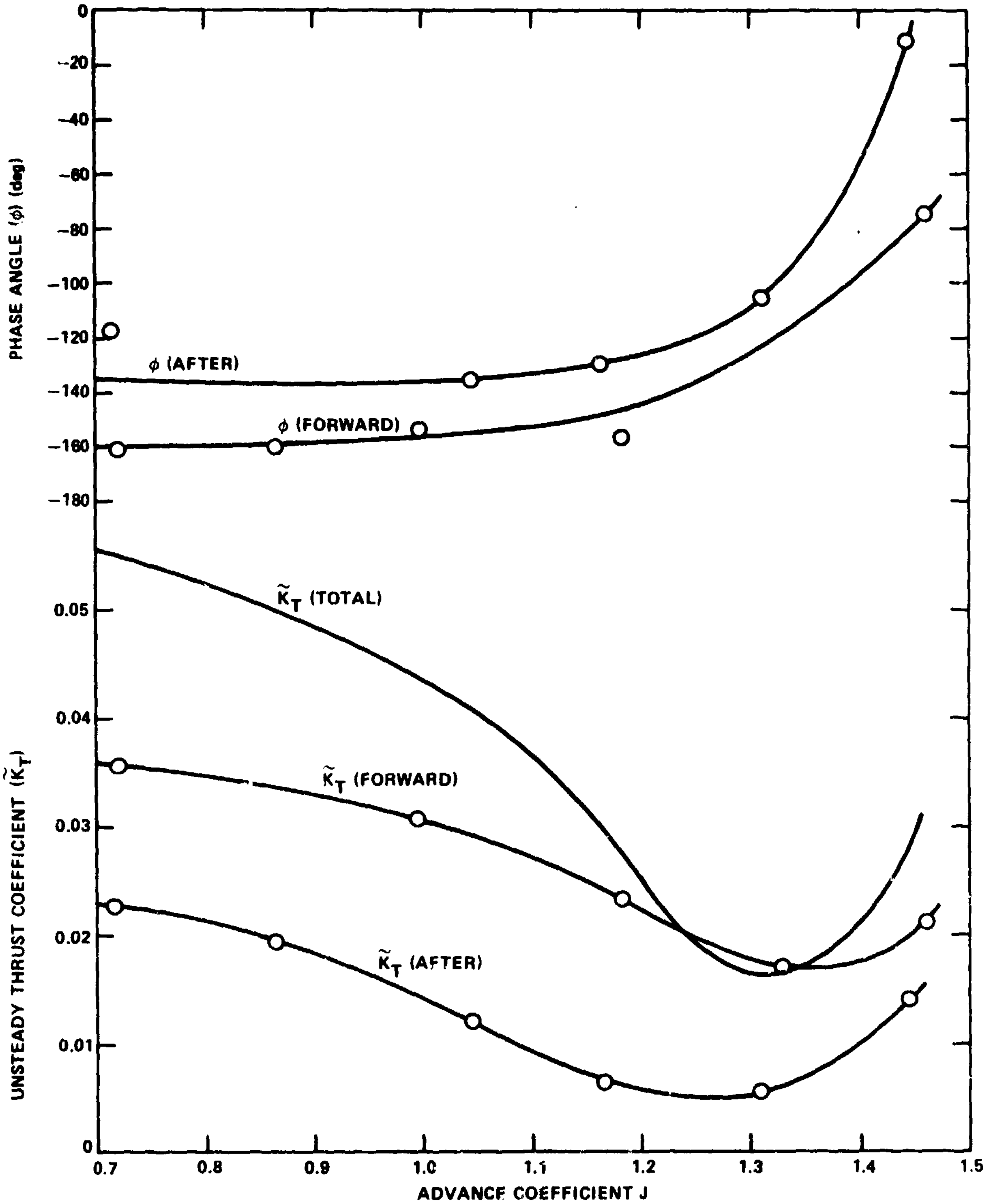


Figure 8 - Open Water Characteristics of Propellers 3686-3849



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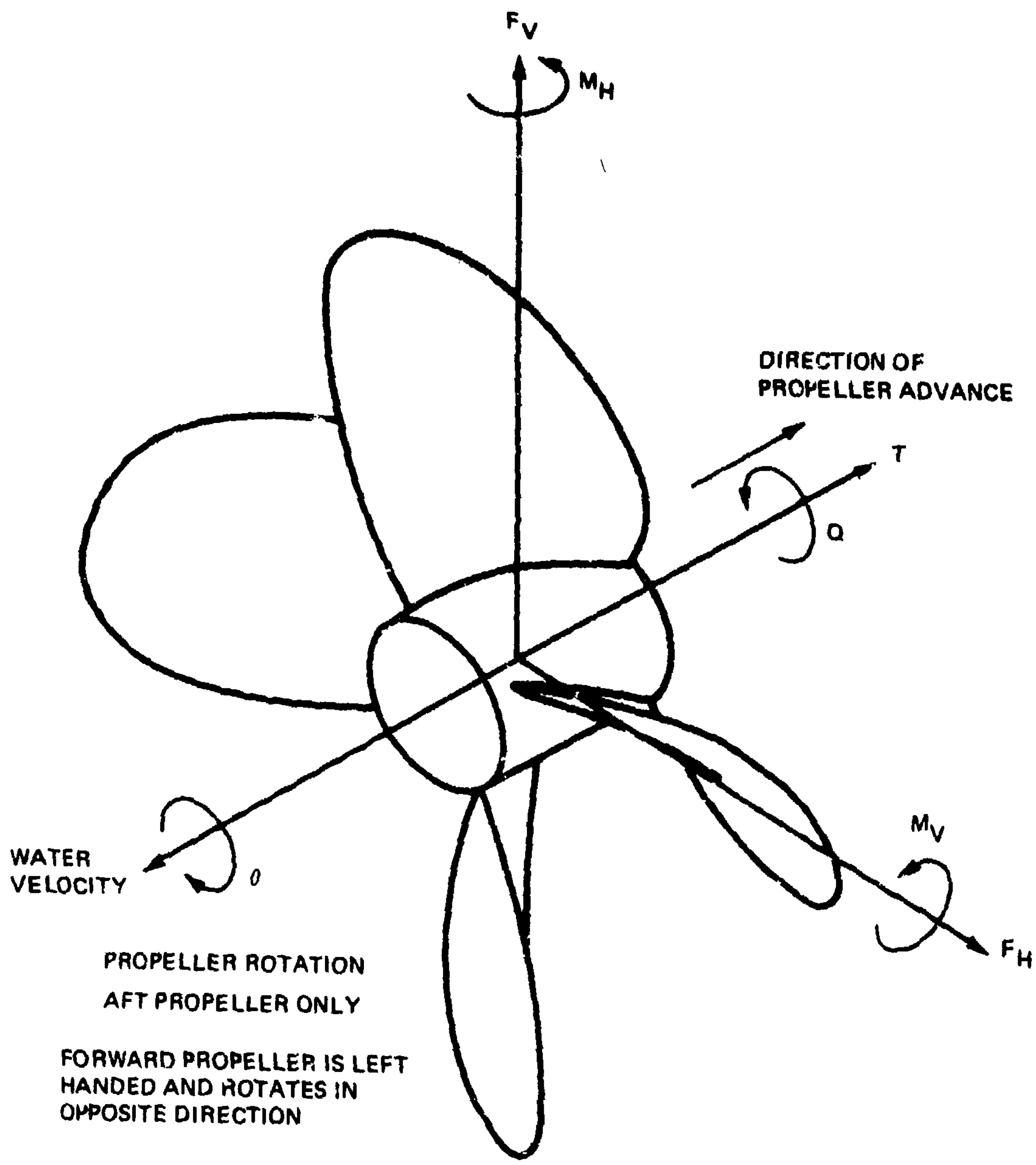

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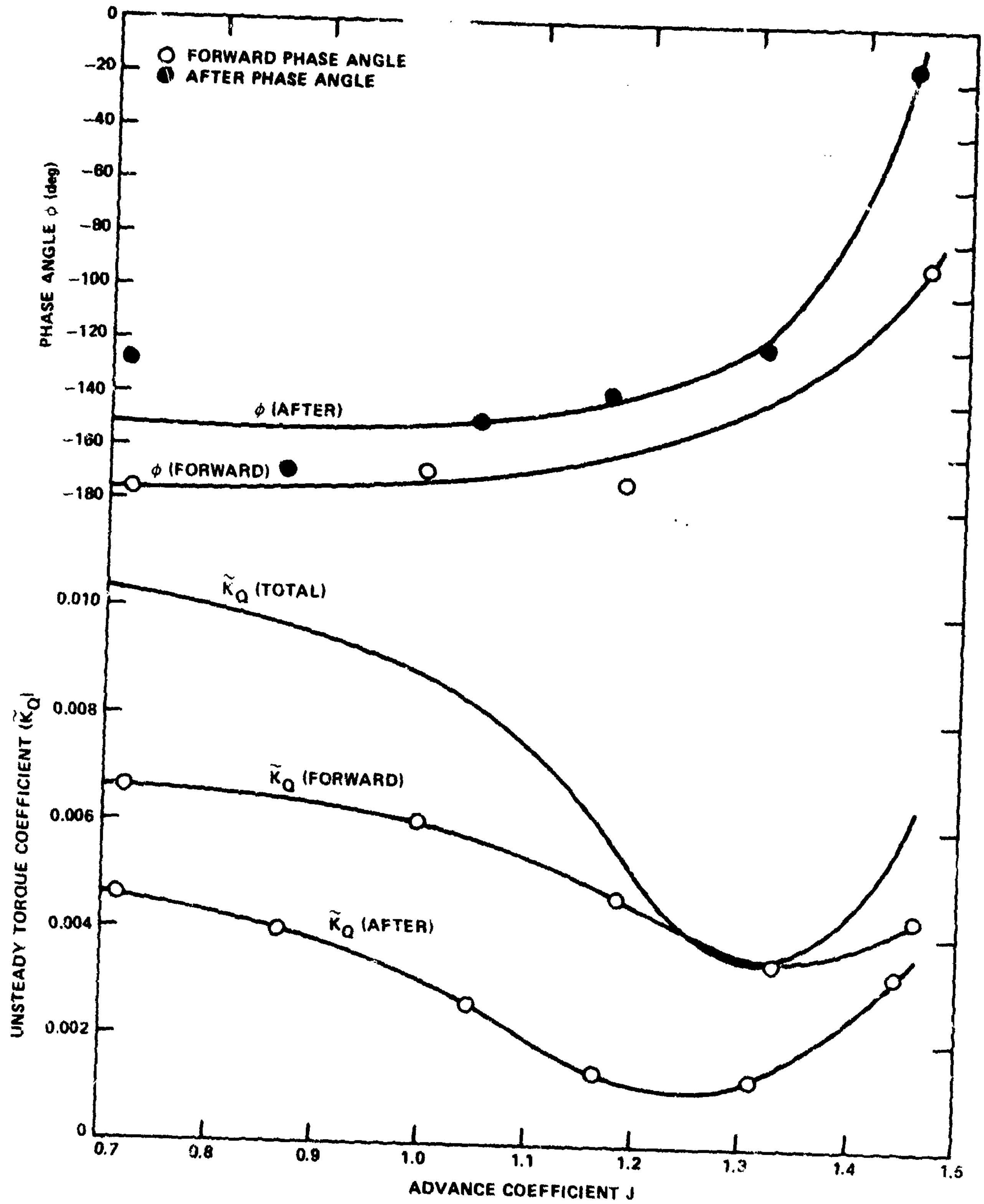

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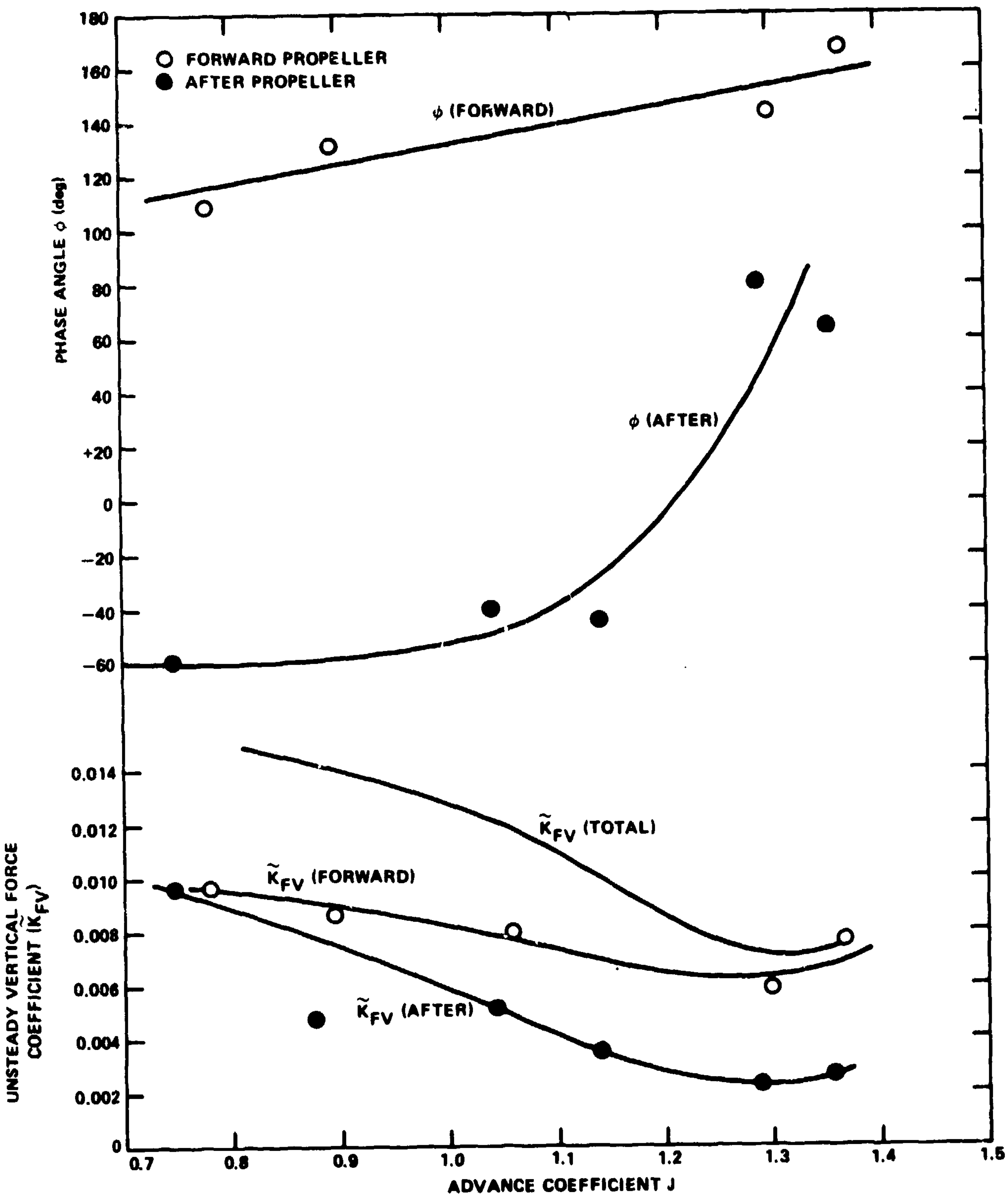

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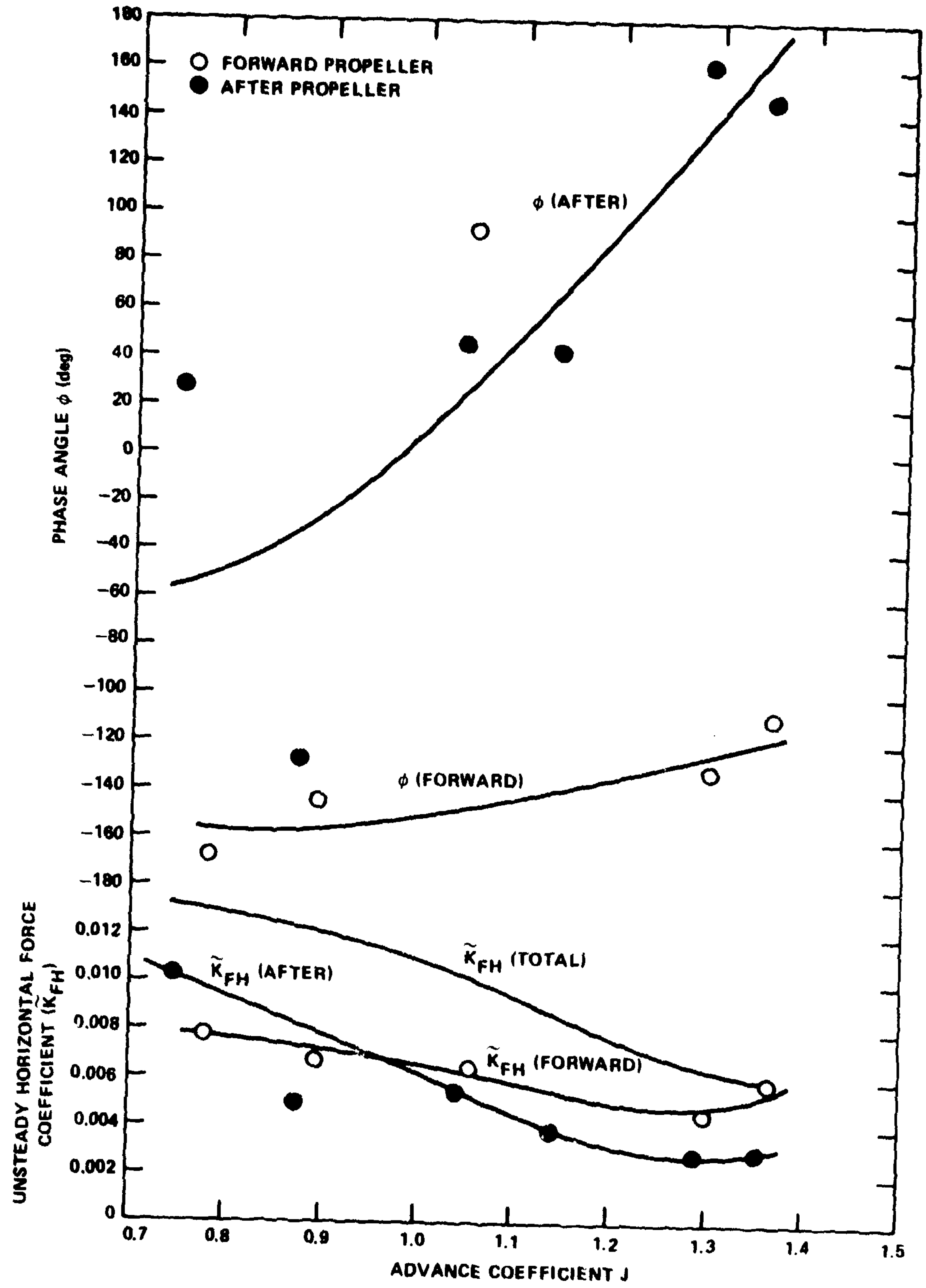
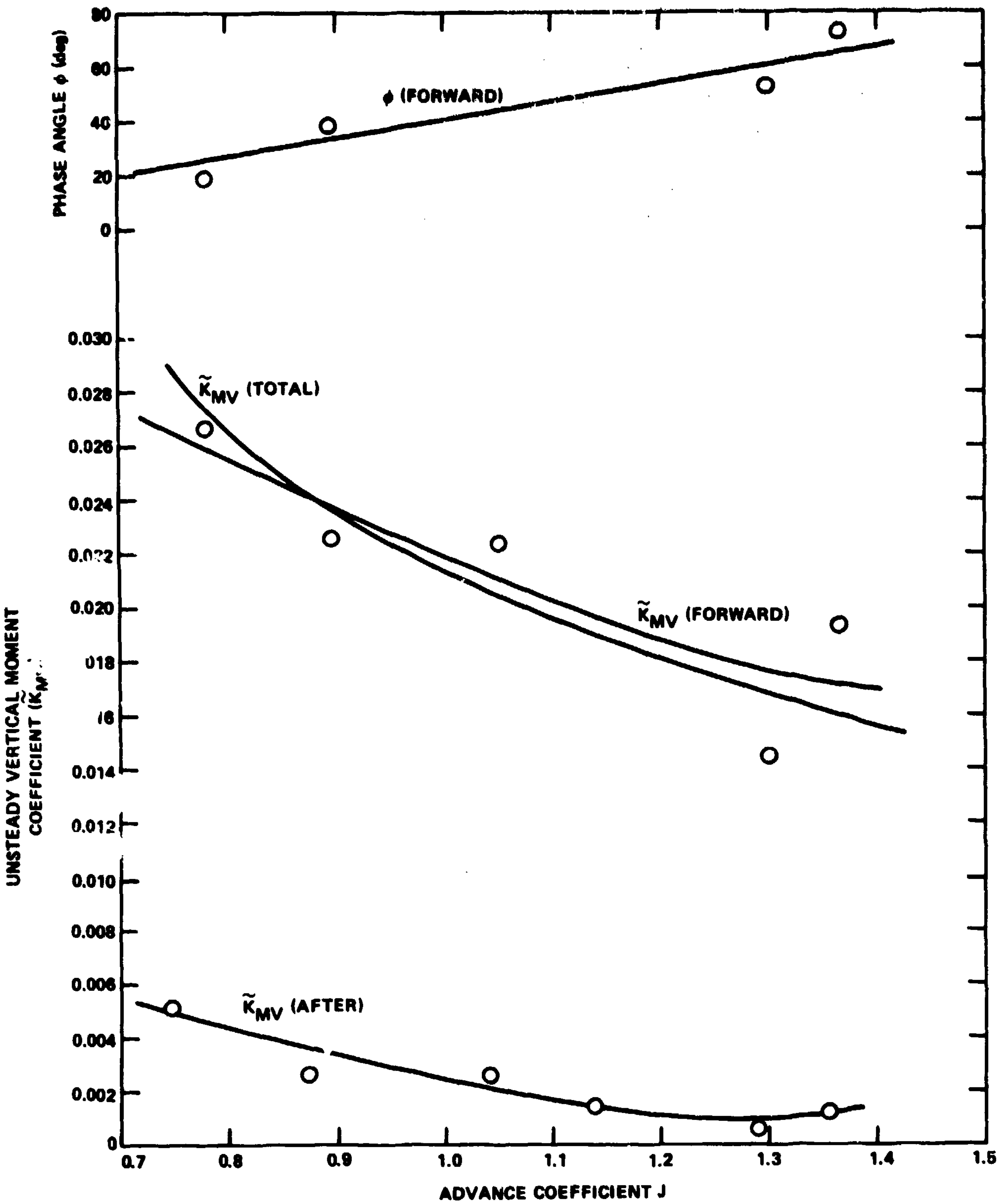


Figure 13 - Unsteady Horizontal Side Forces on 4 × 5 Set at Nine Times Shaft Frequency in Uniform Flow



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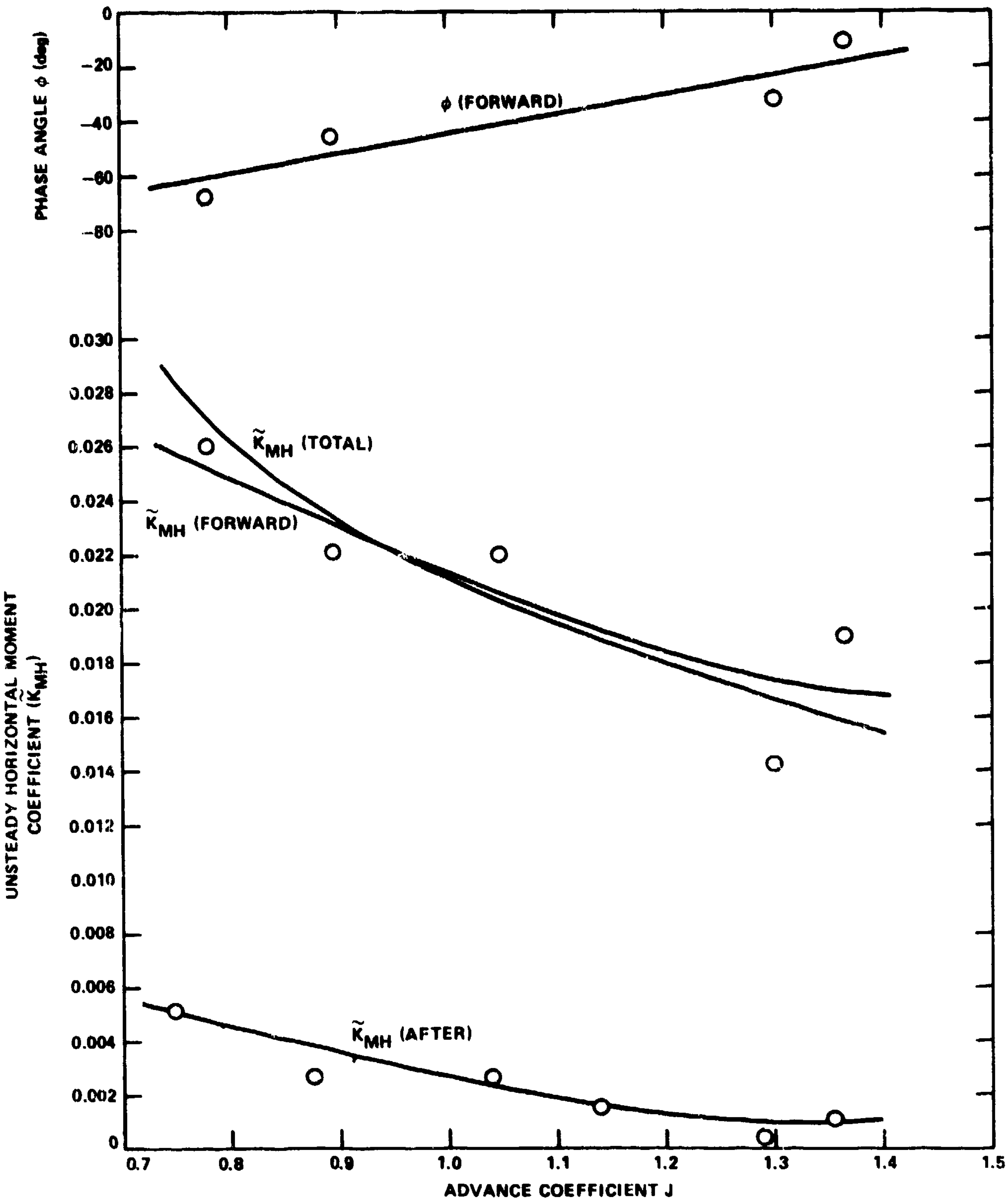
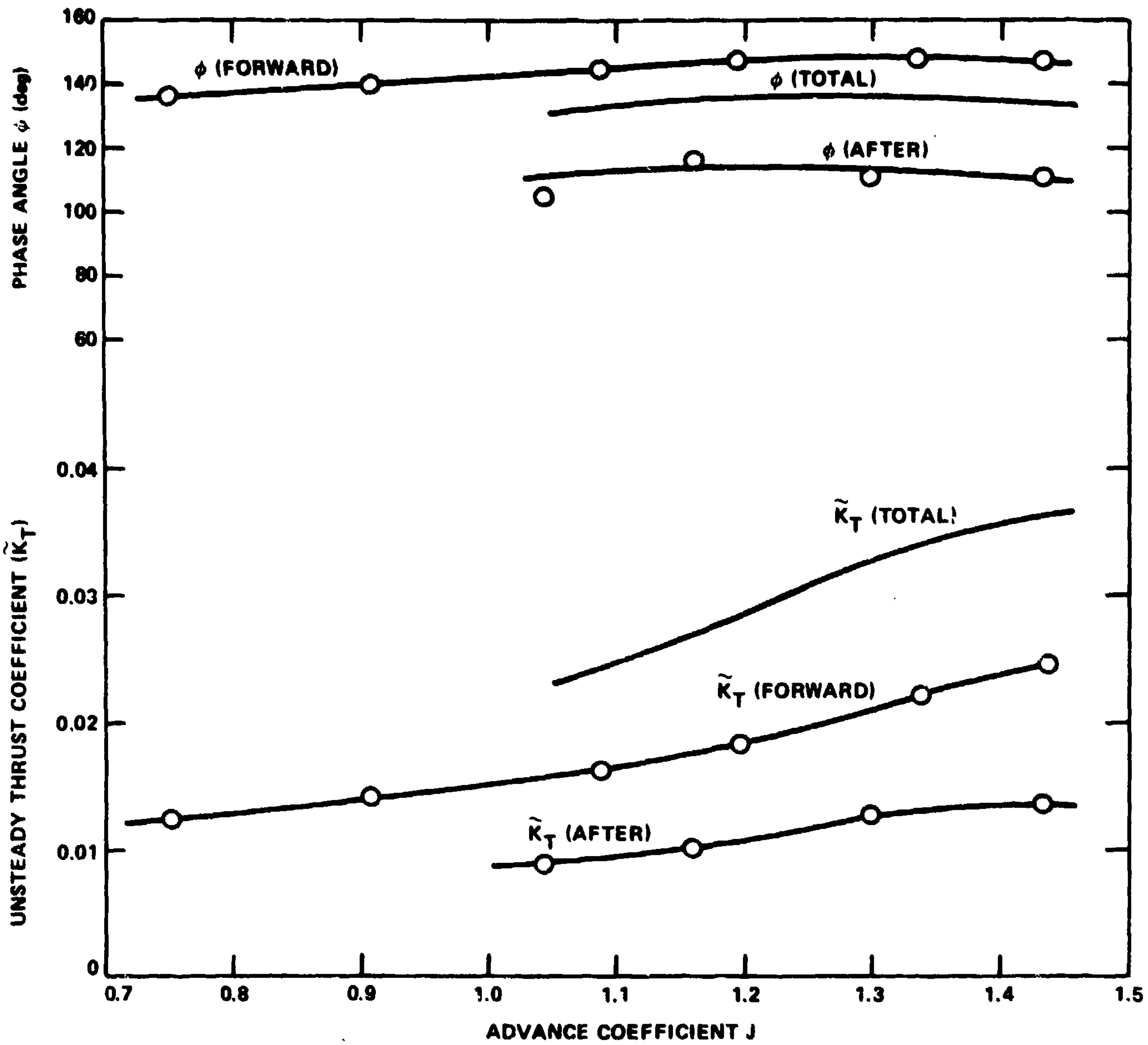


Figure 15 - Unsteady Horizontal Bending Moments on 4 × 5 Set at Nine Times Shaft Frequency in Uniform Flow



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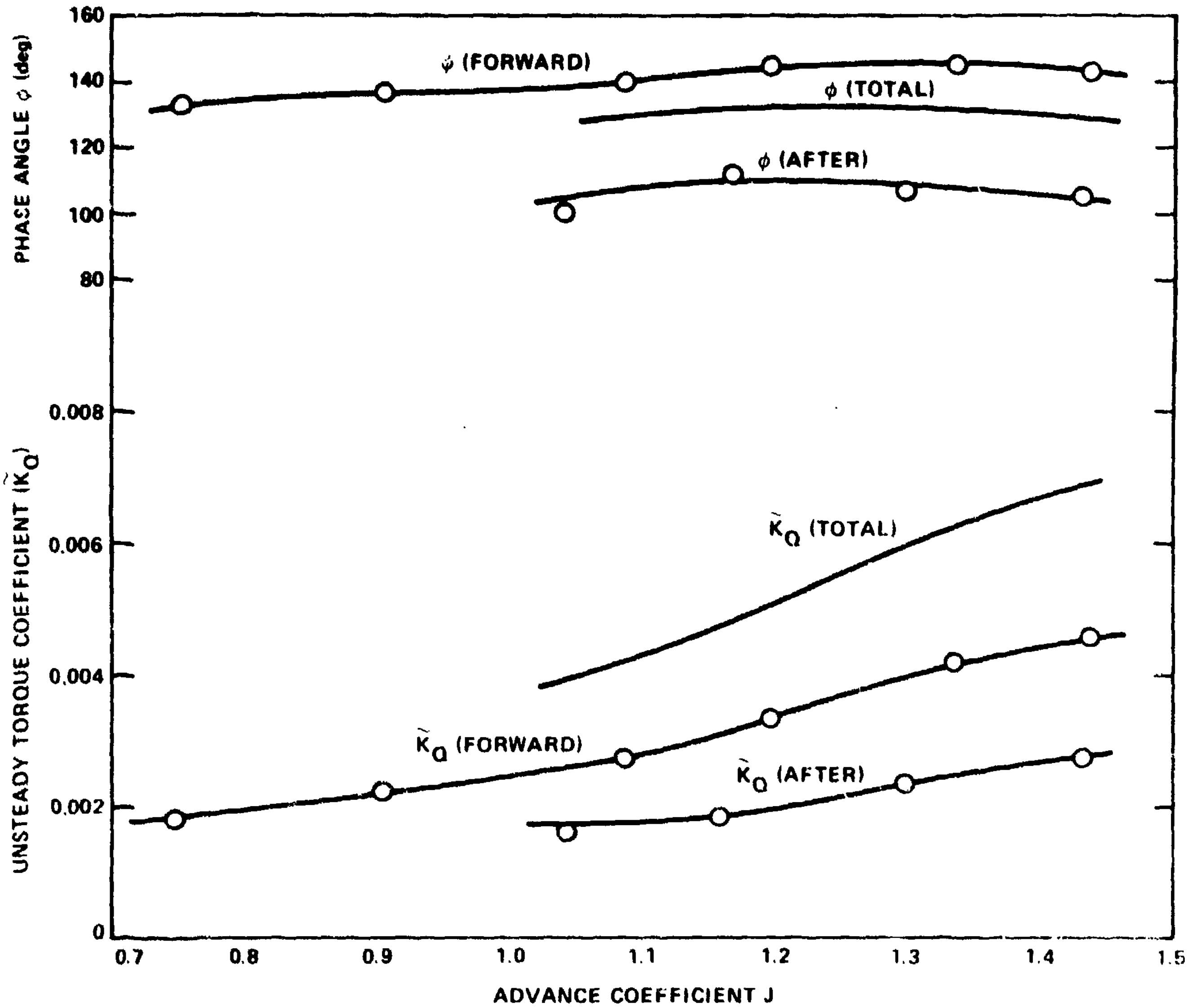


Figure 17 - Unsteady Torque on 4 × 4 Set at 4 Times Shaft Frequency in 4-Cycle Wake

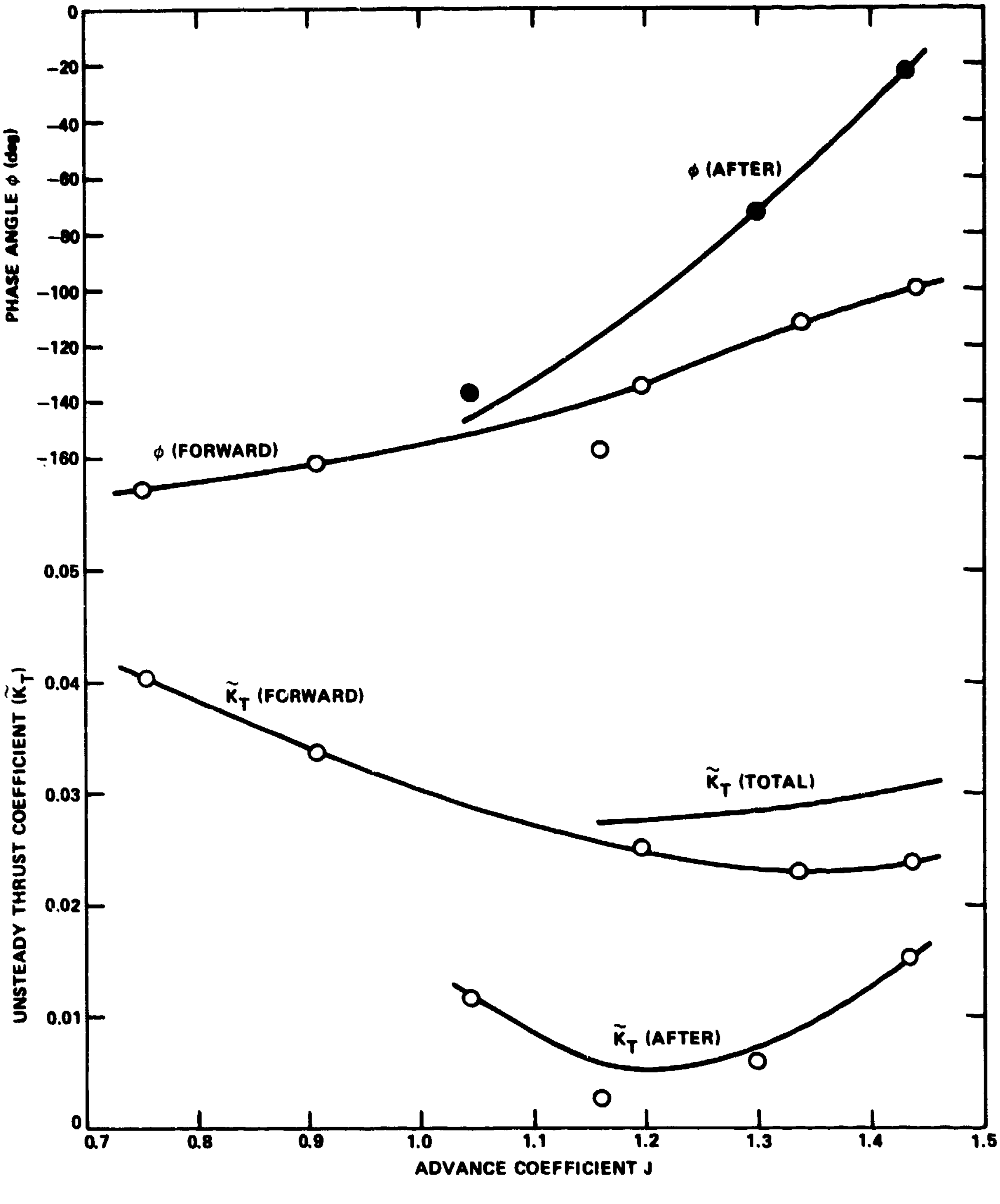
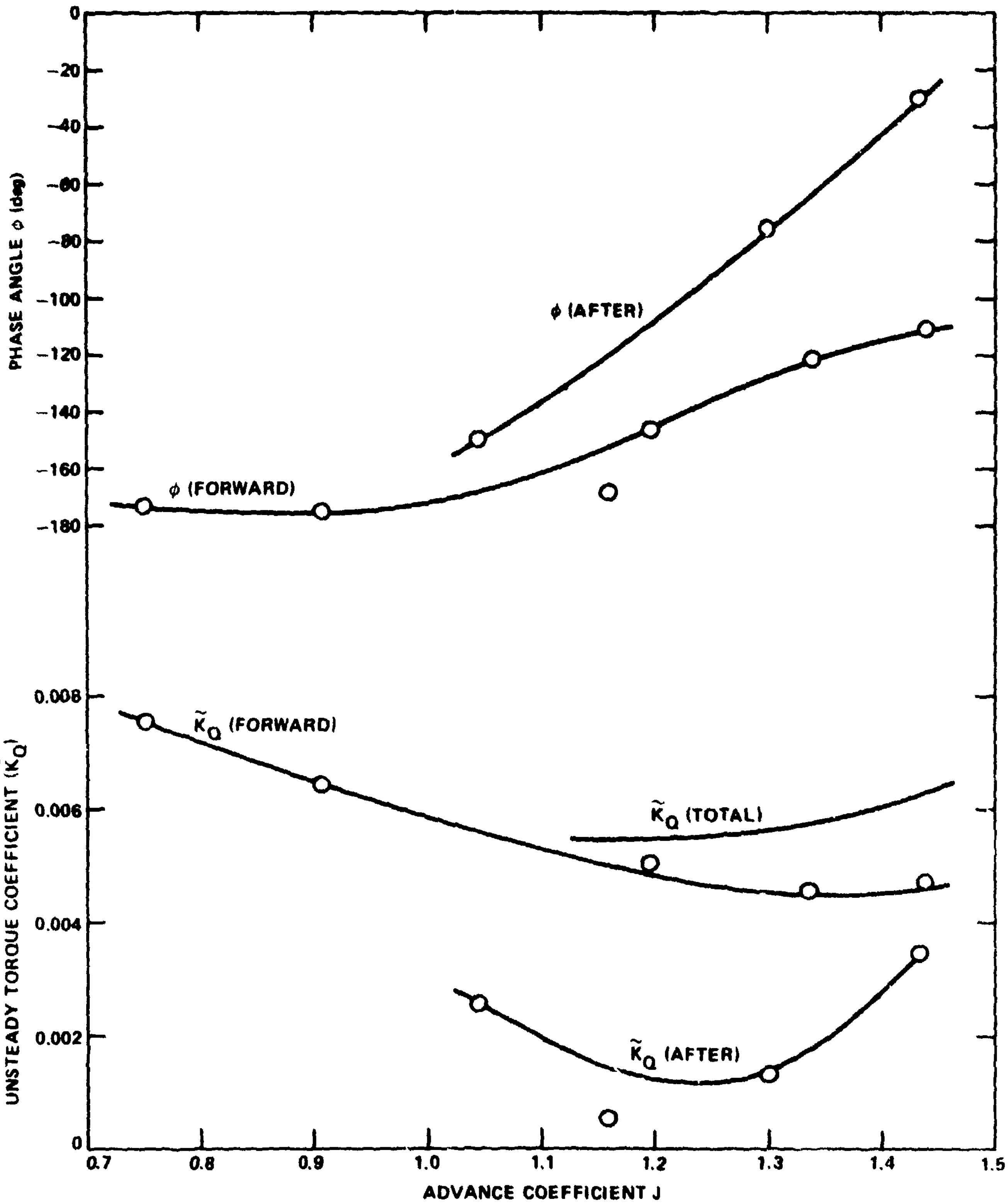


Figure 18 - Unsteady Thrust on 4 × 4 Set at 8 Times Shaft Frequency in 4-Cycle Wake



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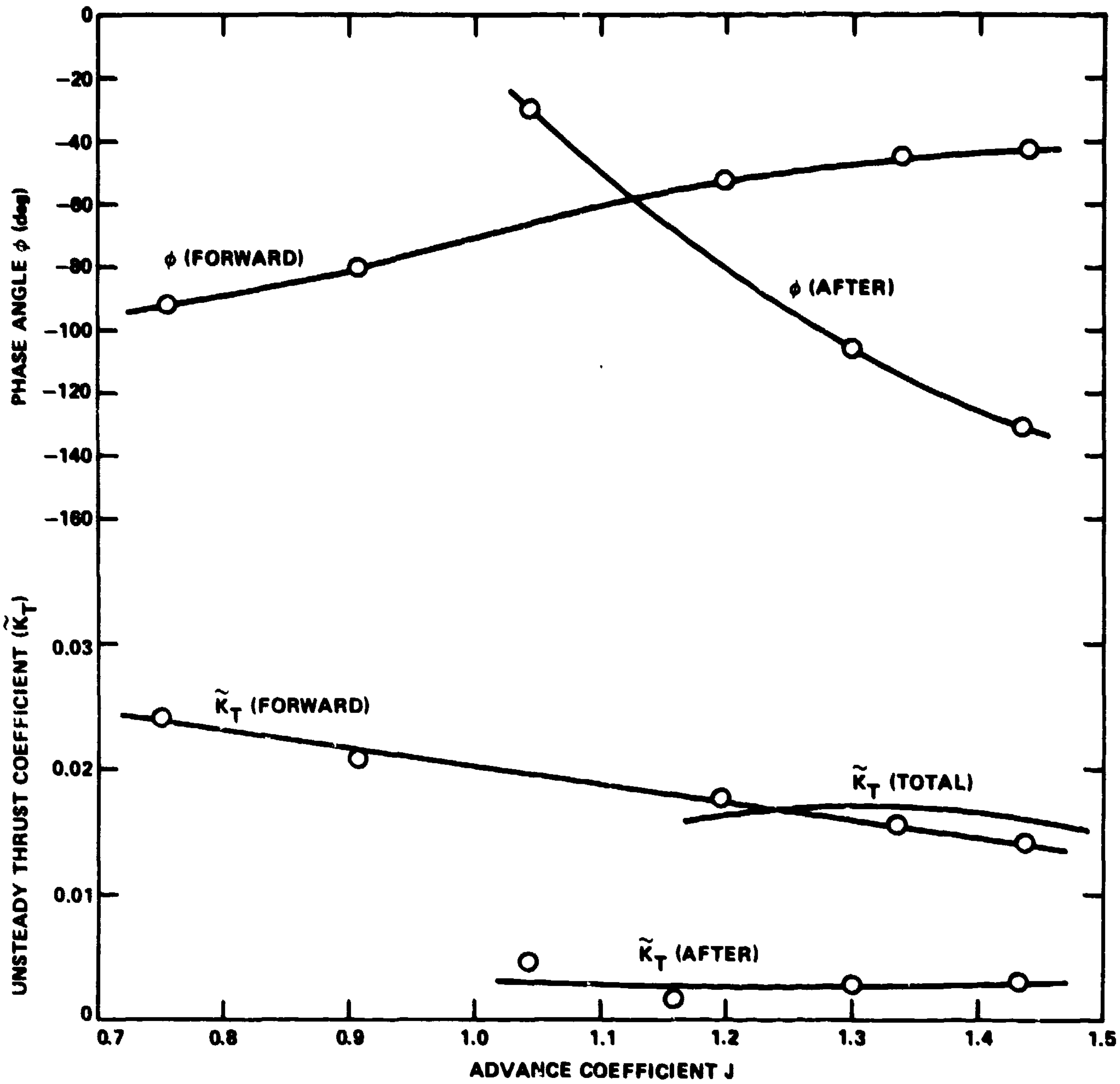

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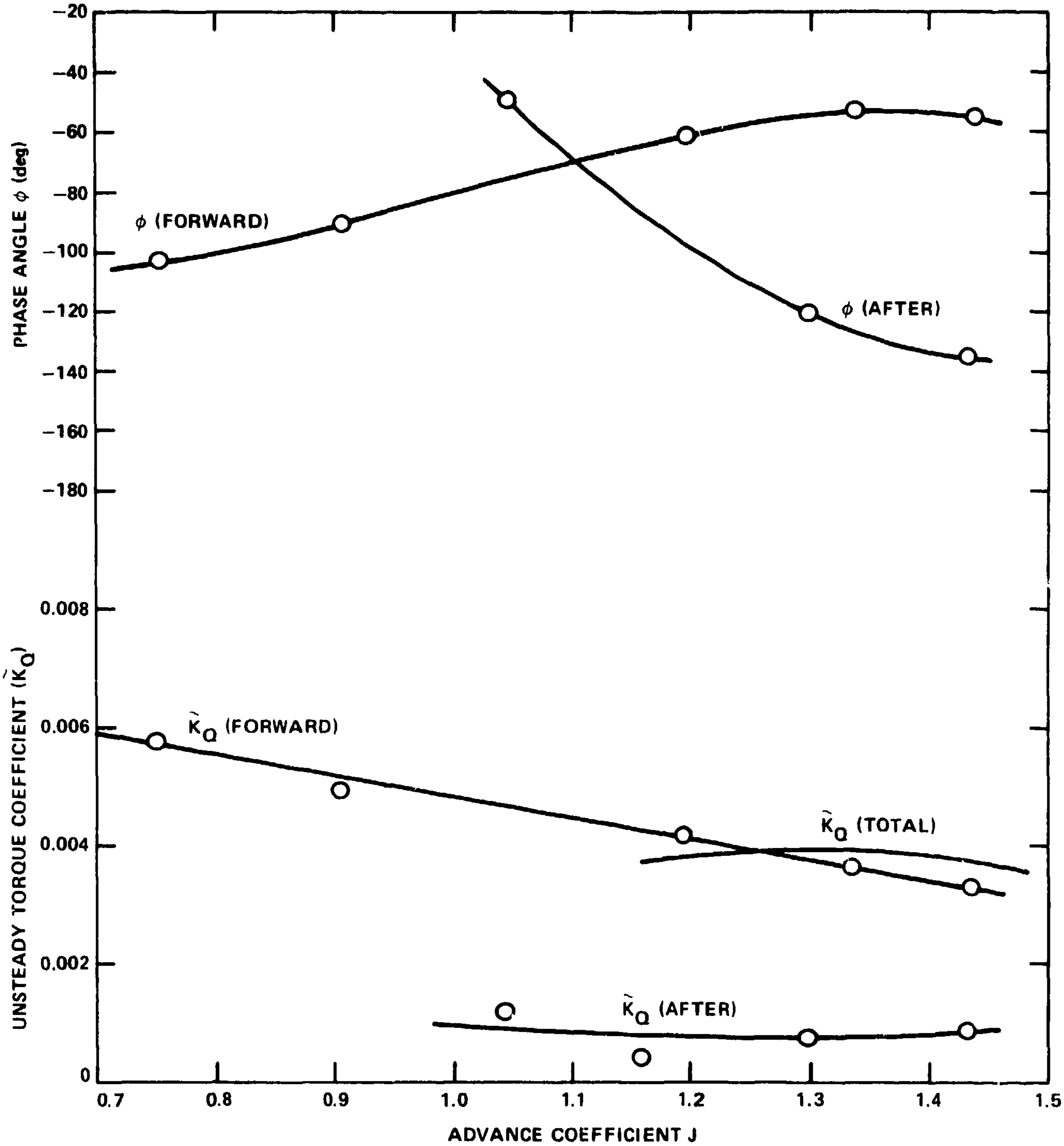

Figure 21 - Unsteady Torque on 4 × 4 Set at 16 Times Shaft Frequency in 4-Cycle Wake

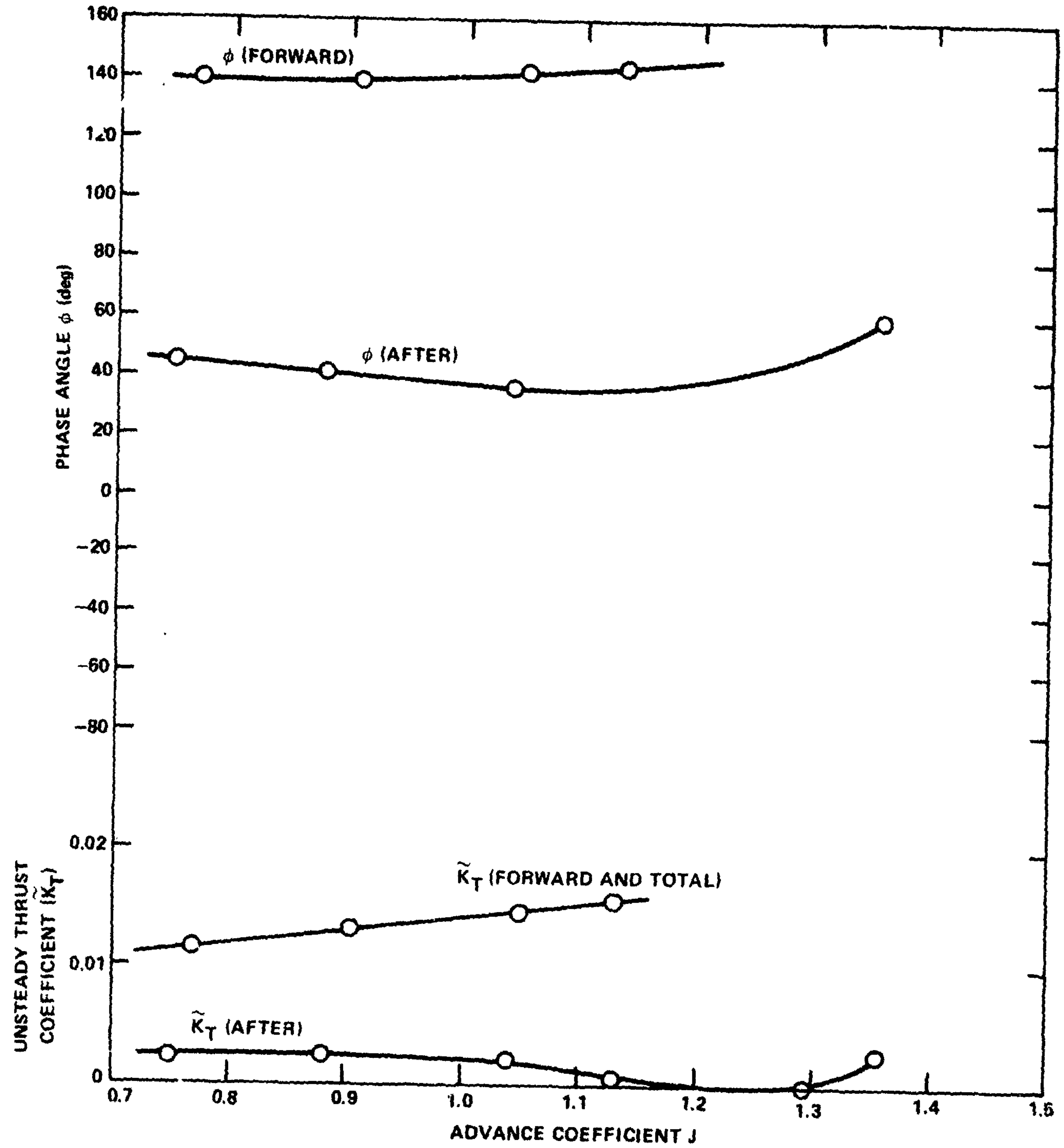

Figure 22 - Unsteady Thrust on 4 × 5 Set at 4 Times Shaft Frequency in 4-Cycle Wake

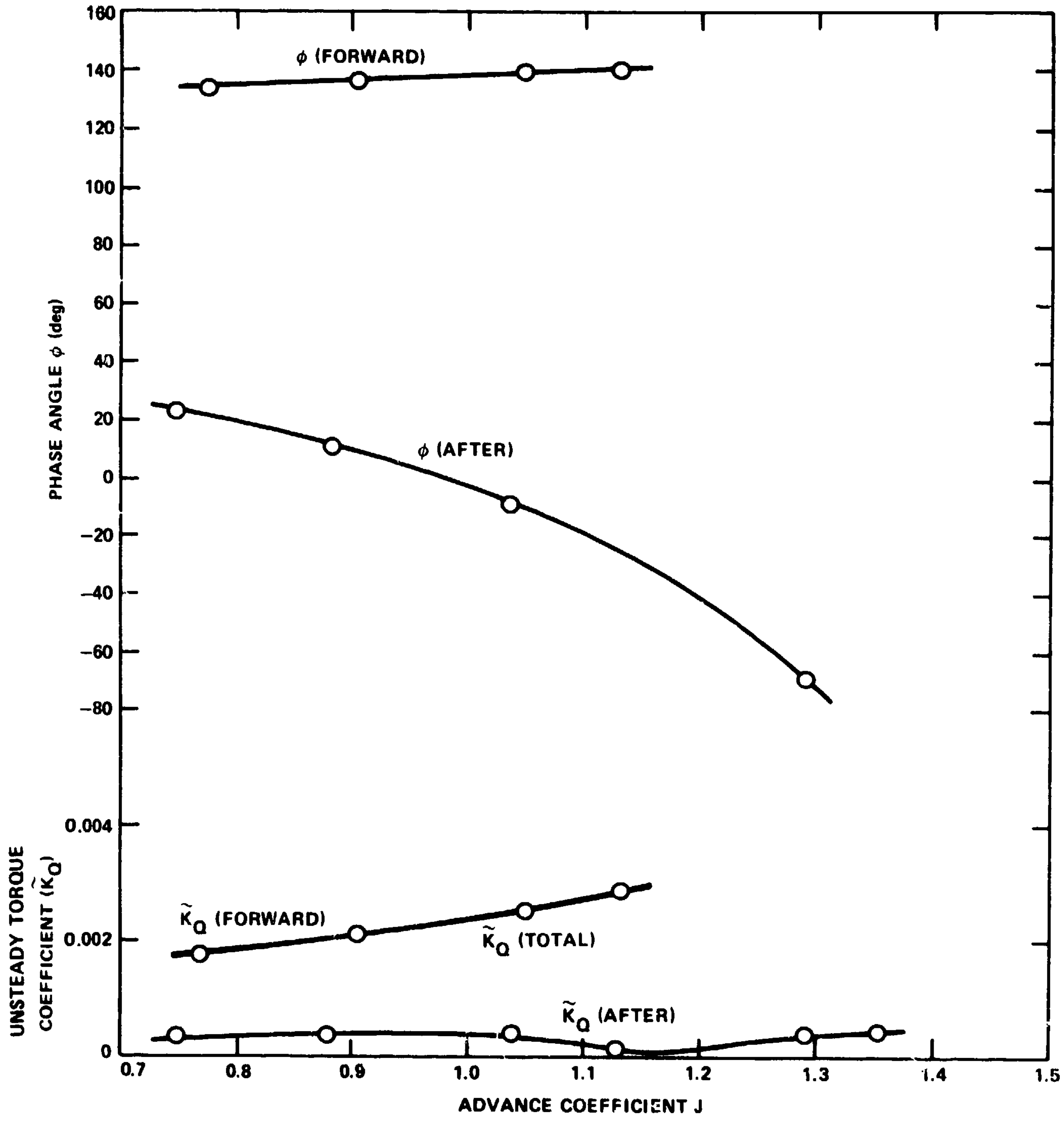

Figure 23 - Unsteady Torque on 4 × 5 Set at 4 Times Shaft Frequency in 4-Cycle Wake

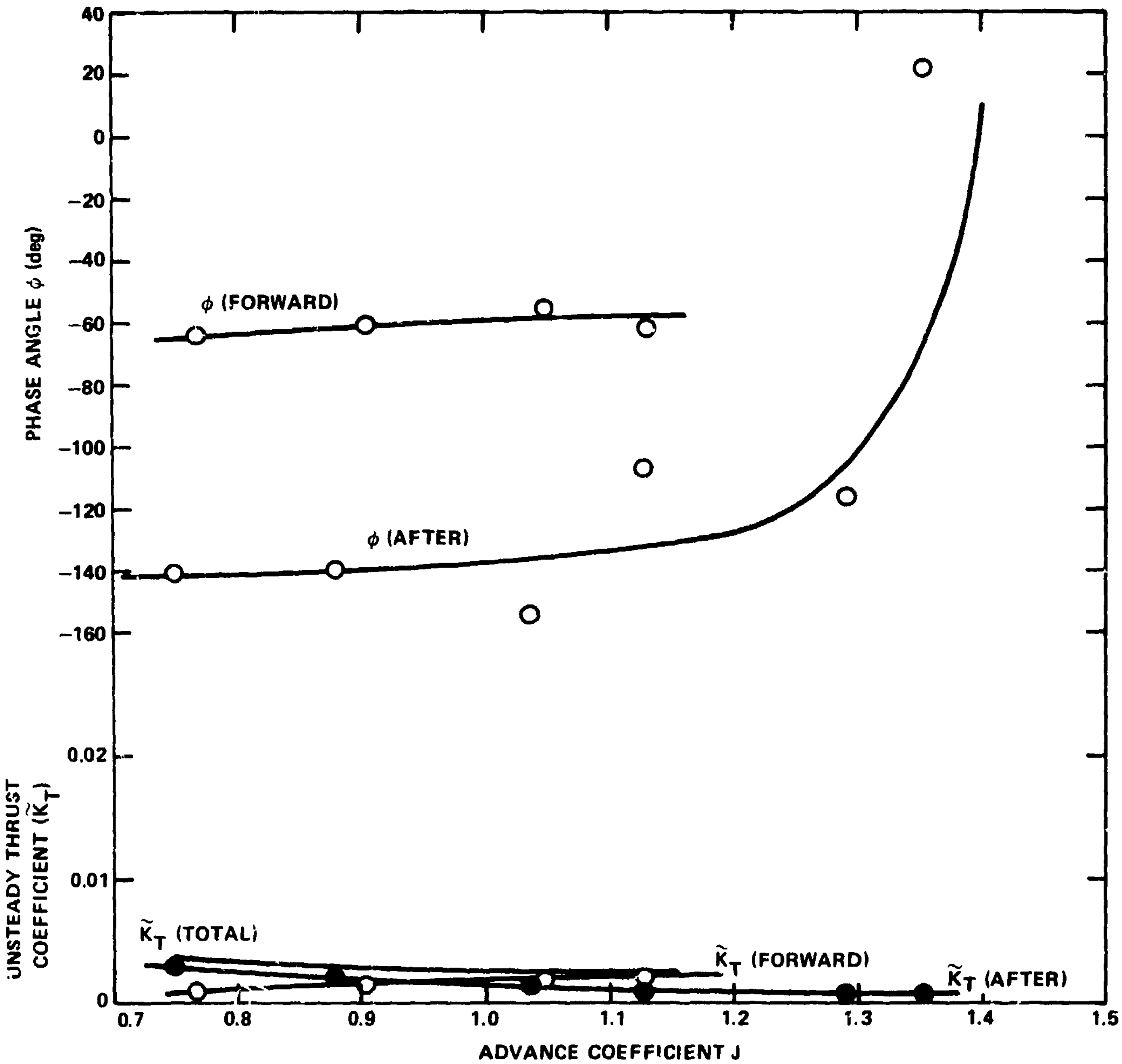

Figure 24 - Unsteady Thrust on 4 × 5 Set at 8 Times Shaft Frequency in 4-Cycle Wake

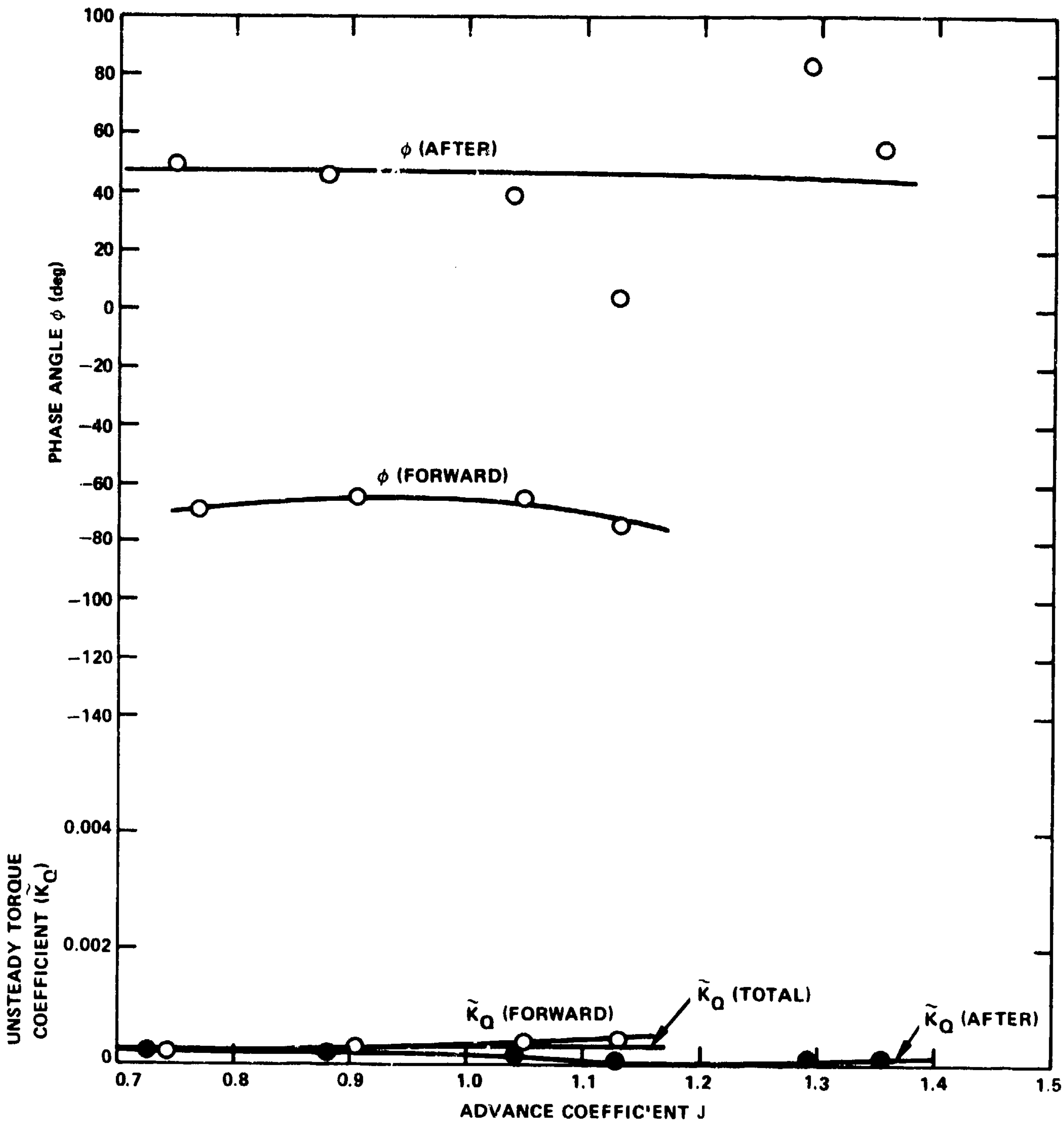

Figure 25 - Unsteady Torque on 4 × 5 Set at 8 Times Shaft Frequency in 4-Cycle Wake

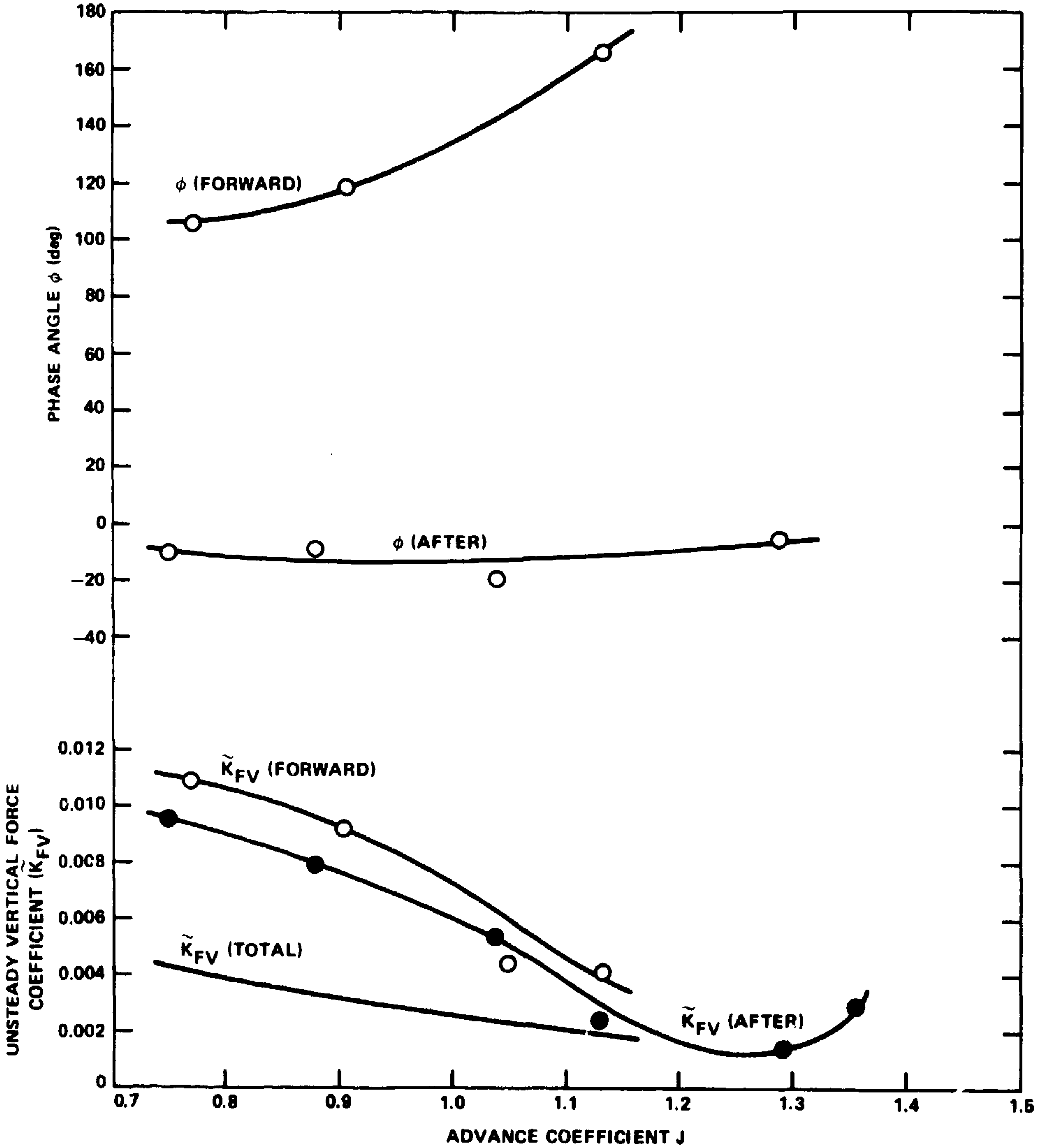

Figure 26 - Unsteady Vertical Side Forces on 4 × 5 Set at 9 Times Shaft Frequency in 4-Cycle Wake

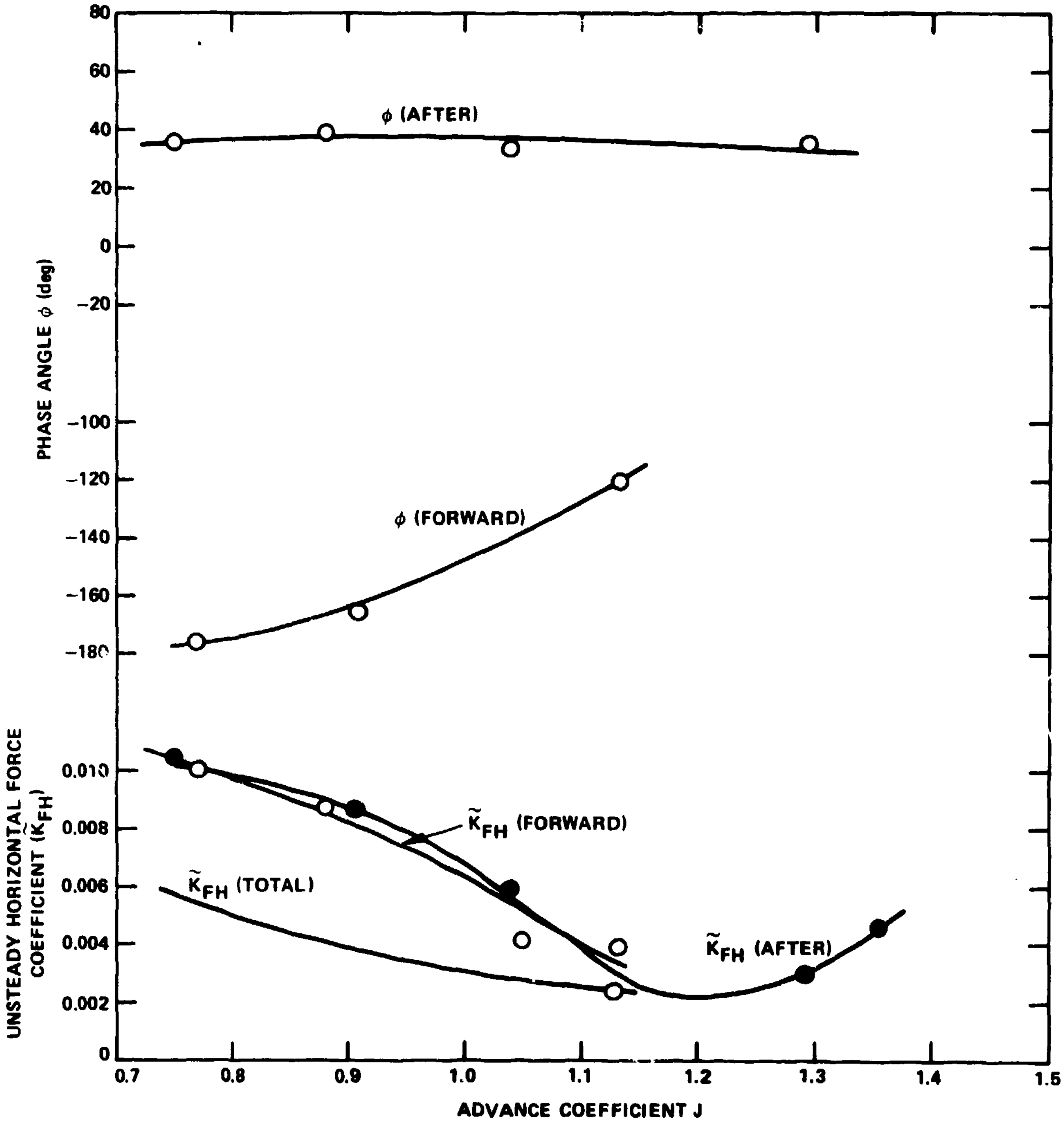

Figure 27 - Unsteady Horizontal Side Forces on 4 × 5 Set at 9 Times Shaft Frequency in 4-Cycle Wake

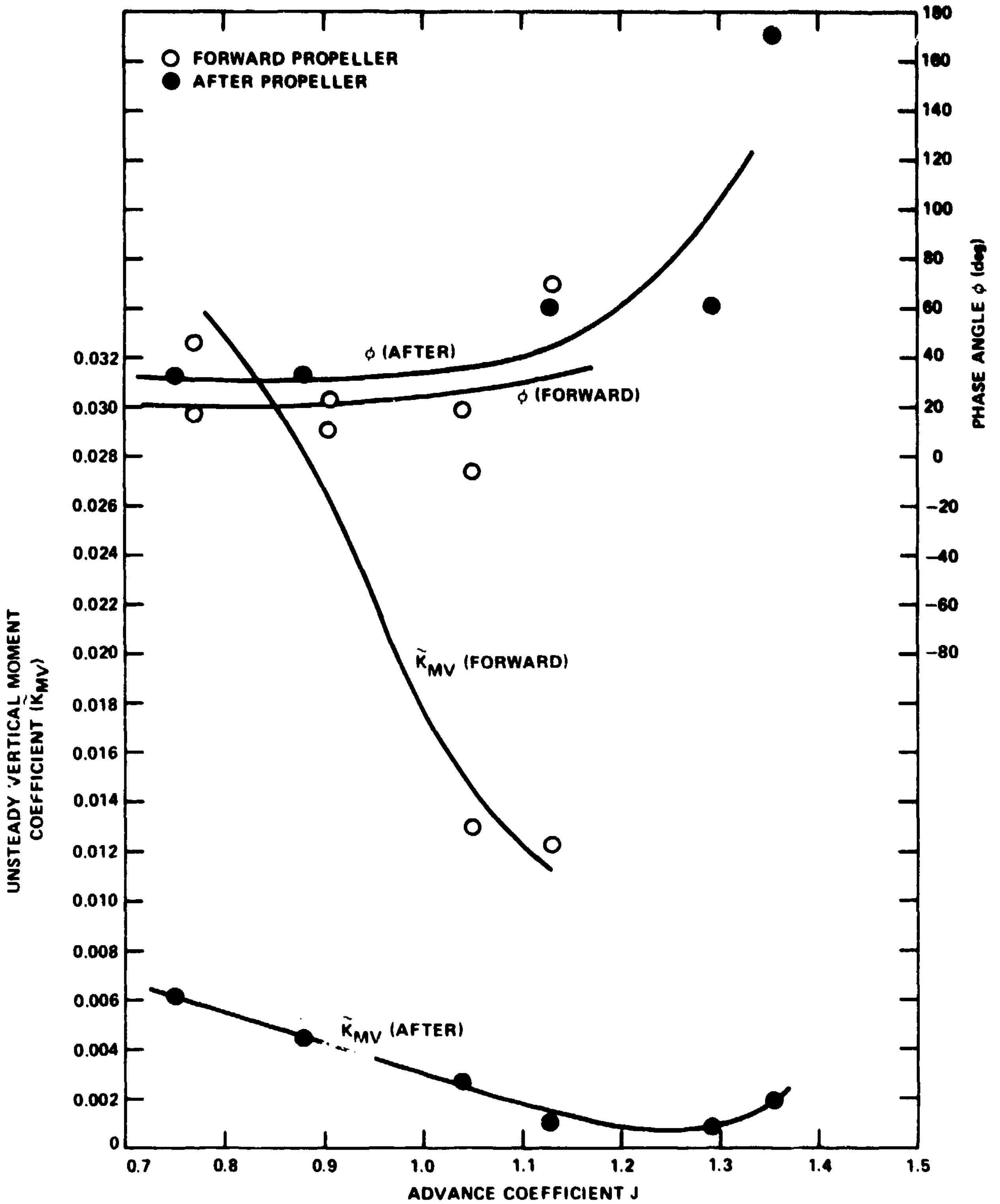

Figure 28 - Unsteady Vertical Bending Moments on 4 × 5 Set at 9 Times Shaft Frequency in 4-Cycle Wake

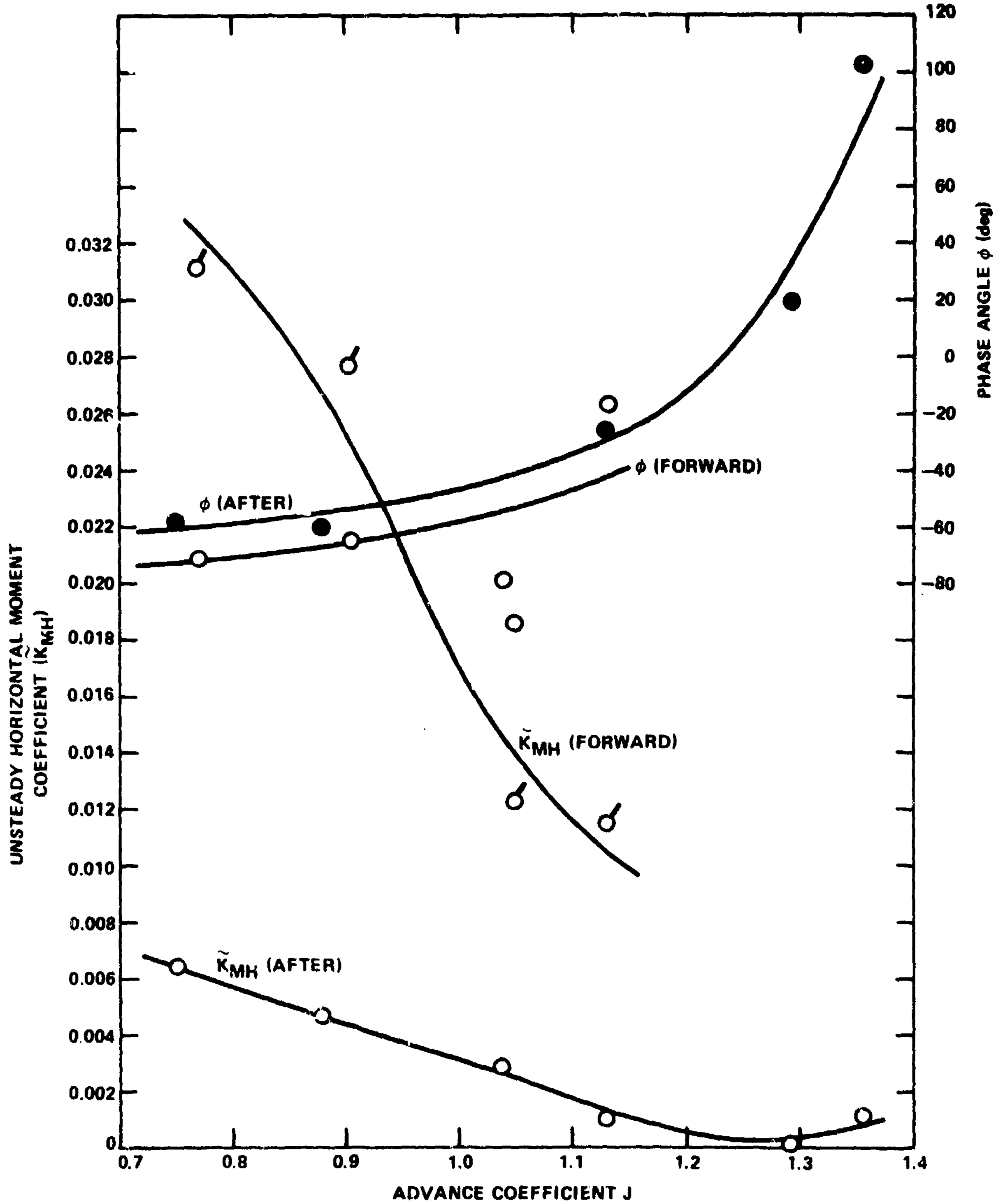

Figure 29 - Unsteady Horizontal Bending Moments on 4 × 5 Set at 9 Times Shaft Frequency in 4-Cycle Wake

TABLE 1 - DESIGN DETAILS OF MODEL PROPELLER 3686

Position	Forward
Number of Blades	4
Diameter	12.017 inches (0.3052 m)
Pitch at 0.7 R	15.510 inches (0.3940 m)
Expanded Area Ratio	0.303
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Left Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.426	0.1075	0.2214	0.0018
0.3	1.396	0.1250	0.1688	0.0364
0.4	1.366	0.1400	0.1321	0.0430
0.5	1.336	0.1548	0.1027	0.0396
0.6	1.310	0.1695	0.0785	0.0353
0.7	1.291	0.1787	0.0604	0.0280
0.8	1.278	0.1750	0.0463	0.0249
0.9	1.269	0.1500	0.0367	0.0206
0.95	1.267	0.1220	0.0344	0.0175
1.00	1.267	---	---	---

TABLE 2 - DESIGN DETAILS OF MODEL PROPELLER 3687A

Position	After
Number of Blades	4
Diameter	11.776 inches (0.2991 m)
Pitch at 0.7 R	15.662 inches (0.3968 m)
Expanded Area Ratio	0.324
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Right Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.289	0.1100	0.2161	0.0020
0.3	1.291	0.1335	0.1581	0.0303
0.4	1.295	0.1530	0.1203	0.0351
0.5	1.302	0.1700	0.0935	0.0339
0.6	1.311	0.1823	0.0727	0.0319
0.7	1.326	0.1898	0.0569	0.0280
0.8	1.344	0.1833	0.0442	0.0242
0.9	1.361	0.1520	0.0362	0.0216
0.95	1.369	0.1220	0.0345	0.0199
1.00	1.376	---	---	---

TABLE 3 - DESIGN DETAILS OF MODEL PROPELLER 3849

Position	After
Number of Blades	5
Diameter	11.785 inches (0.2993 m)
Pitch at 0.7 R	15.168 inches (0.3853 m)
Expanded Area Ratio	0.379
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Right Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.169	0.1075	0.2214	---
0.3	1.207	0.1250	0.1688	0.0269
0.4	1.243	0.1400	0.1321	0.0299
0.5	1.277	0.1543	0.1027	0.0290
0.6	1.288	0.1695	0.0784	0 0273
0.7	1.287	0.1785	0.0604	0.0238
0.8	1.293	0.1750	0.0463	0.0208
0.9	1.321	0.1500	0.0367	0.0182
0.95	1.349	0.1220	0.0344	0.0176
1.00	1.390	---	---	---

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